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**Draft Program Plan for TNS—The Next Step
After the Tokamak Fusion Test Reactor**

Part II—R&D Needs Assessment

Oak Ridge TNS Program Staff

OAK RIDGE NATIONAL LABORATORY
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Fusion Energy Division

DRAFT PROGRAM PLAN FOR TNS — THE NEXT STEP
AFTER THE TOKAMAK FUSION TEST REACTOR
PART II — R&D NEEDS ASSESSMENT

Date Published: December 1977

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Oak Ridge TNS Program Staff

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REA

This assessment is Part II of a four-part report which comprises the Draft Program Plan for TNS. The other parts of the report are

ORNL/TM-5982	Part I Summary
WFPS/TME-044	Part III Project Specific R&D Needs
ORNL/TM-5984	Part IV Program Planning

DRAFT PROGRAM PLAN FOR TNS — THE NEXT STEP
AFTER THE TOKAMAK FUSION TEST REACTOR

PART II — R&D NEEDS ASSESSMENT

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FOREWORD

The Next Step (TNS) Program, established by ERDA's Division of Magnetic Fusion Energy at ORNL in early 1976, has two principal objectives:

1. To demonstrate in a timely fashion a fusion reactor core that can be extrapolated to an economically viable fusion reactor.
2. To provide a near-term means of focusing the efforts of the National Fusion Program to achieve the first objective.

This first draft of an attempt to outline a TNS program plan addresses the second objective. The draft program plan is presented in four parts:

PART I Summary

PART II R&D Needs Assessment

PART III Project Specific R&D Statements

PART IV Program Planning

This assessment was developed initially in an intense few-week period, based upon the understanding and information which has been built up at ORNL and Westinghouse over the preceding years by participation in the Fusion Program in general and in the Tokamak Fusion Test Reactor (TFTR) [both the Feasibility/Burning Experiment (F/BX) and the Two Component Torus (TCT)], the Experimental Power Reactor (EPR), and prior TNS studies, in particular.

In attempting to develop a program plan, two kinds of information were included in the assessment, namely, current status and extrapolation. With rapid technical progress being made in many laboratories, elements of the current technical status should be reevaluated on perhaps a semiyearly or yearly basis. Since the fusion program is tied strongly to the nation's energy program in general, the extrapolation can change and does change on a much more rapid time scale. In particular, this "snapshot" of the TNS support program taken in January-February 1977 does not take into account budget changes discussed in the same period and does not reflect the evolution of schedular planning that occurred

in the March-April 1977 period. As a result, some of the implications for action based upon the targeted FY-1980 line item are not longer meaningful, whereas the basic arguments still apply but to a line item some years later.

This document is, therefore, issued principally for comment and discussion, rather than as a definitive statement.

ACKNOWLEDGMENTS

Development of the information contained in this Draft Program Plan has resulted from the efforts of many people in the fusion community, who invested from a day to a month or more in this task. The principal contributors are members of the Oak Ridge TNS Program team, both at ORNL and Westinghouse, who have devoted their full efforts to this task for many weeks. Bringing specific technical expertise to the development for varying lengths of time have been individuals from the ORNL Fusion Program and from various institutions around the country. Preparation of Part II has received the focused attention of both the Fusion Energy Division's Plasma Theory Section, especially J. D. Callen, F. B. Marcus, J. A. Rome, Y-K. M. Peng, and A. T. Mense, and G. G. Kelley for Sect. 3 and the attention of a wide range of representatives from the fusion program's technology groups in the Fusion Energy Division, Chemical Technology Division, Neutron Physics Division, and Metals and Ceramics Division for Sect. 4. In Sect. 4, T. E. Shannon, W. R. Becraft, P. T. Spampinato, G. A. Krist, and R. Wysor were responsible for coordinating the many elements of the work, and W. B. Wood produced the program charts. The participation of teams who were in Oak Ridge during this intensive period from the LASL-UT OH Study, the NBS Low Temperature Materials Program, the C. S. Draper C&I Program, as well as specific critical comments of individuals from PPPL and Science Applications, Inc., is much appreciated. From ERDA-DMFE, J. O. Neff and his colleagues have provided valuable guidance and comments; S. Waddle and G. Benedict have participated in the review process from ERDA-ORO.

Throughout this exercise, J. F. Clarke has provided valuable direction and strong support. The high level of timely, professional support from the secretarial and Technical Publications staffs has made rapid dissemination of this information possible.

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ABSTRACT

The information contained in this document represents the brief but intensive efforts of the Oak Ridge TNS Program Team^{*} to answer the following questions:

1. Is there an adequate basis of R&D support for the TNS program as a central, ambitious goal for the fusion program?
2. What are the principal gaps in the current and projected R&D program?
3. What must be done to permit operation of TNS in the mid 1980s?

The findings of our preliminary study provide these answers to the questions:

1. The physics and technology base does exist from which to start the TNS design as a central fusion program goal.
2. We have specific recommendations for new emphasis in certain physics and technology areas to minimize R&D program gaps.
3. TNS conceptual design must be started now, and a close look at organizing the fusion program around a TNS project is an essential need to support operation in the mid 1980s.

The first point — support base — is addressed in this volume, Part II, and somewhat in Part III. Significant strides have been made in both fusion physics achievement (in plasma density, energy confinement, plasma temperature, and effective impurity level) and operational understanding. Even though we do not now have a working theoretical framework that allows us to extrapolate present-day plasma parameters into the low-collisionality, high-density fusion plasma regime with confidence, we can examine many of the specific physics areas expected to be important

^{*}The Oak Ridge TNS Program Team is made up of individuals from ORNL and UCC-ND Engineering, Westinghouse Fusion Power Systems Department, and key industrial participants. ORNL's Fusion Energy Division provides technical management and plasma physics, plasma engineering, and fusion technology with support in fusion reactor technology from ORNL's Neutron Physics, Chemical Technology, and Metals and Ceramics divisions; UCC-ND's Engineering organization provides design engineering direction and review and project engineering. Westinghouse provides the engineering design team, and individuals from General Electric Co., Grumman Aerospace Co., Westinghouse Electric Co., and Burns & Roe, Inc., provide special technical expertise.

in the TNS design process and begin to specify the kind of information required in that area during each major design period. Some areas (e.g., impurity control) require more study before a clear picture of the problem itself can be developed, and other areas (e.g., ash removal) might first be properly addressed in TNS. Sound technology program bases from which to start exist in the three key areas for TNS — i.e., toroidal field (TF) magnets for the Large Coil Program (LCP), 150-keV beams for TFTR, and tritium handling for the Tritium Systems Test Assembly (TSTA). Adequate power electronics capability exists in industry for the poloidal field (PF) system requirements, although preliminary estimates indicate at high cost.

On the second point — principal gaps — those areas known to require more knowledge and increased emphasis are the subject of current and planned investigation, with three principal exceptions in physics and between seven and fifteen exceptions in technologies. These exceptions form the principal gaps. The delineation of these exceptions and the suggested remedial actions are detailed in this volume, Part II.

- A comprehensive impurity and particle control plan must be formulated on a timely basis to identify the best way to proceed in this most uncertain area, which has been made even more critical by recent cross-section data calculations;¹ rapid implementation of the plan must follow if the gap is to be filled.
- The need for experimental investigation of configuration ~~maintenance~~ and optimization in high- β , high temperature plasmas is not now being met in any existing or near-term facility; in the near-term (i.e., about 3 years) the two facilities closest in capability, namely Doublet III and PDX, will be addressing specifically Doublet shapes and divertor operation respectively. Present capability does include the ability to develop but not to maintain the configuration of interest. Therefore, either a revision of current objectives for the relevant, existing devices or consideration of a new device is called for.
- The applied theoretical program in impurity dynamics, plasma transport, and, most critically, coupled equilibrium, stability, transport, and heating simulation of ignition scenarios must be intensified in the existing plasma theory base program. These applications-oriented efforts, addressing the most uncertain problem areas in TNS plasma physics, are essential to make transport code predictions reliable and complete.

- Seven areas need initiation of programs or new emphasis in exploratory studies to ensure an acceptable technology base for TNS final design under any scenario.

<u>Programs</u>	<u>Studies</u>
Compound gas pump development	Limiter materials improvement
Neutral beam (NB) switch tube pulse lengthening	Plasma configuration sensing and control
Increased NB power and pulse length per source	Abnormal control operations
Poloidal field (PF) electrical systems (for cost reductions)	

- Six other programs might need increased emphasis depending upon TNS design decisions. (For this study aimed at the earliest schedule, it was judged necessary and sufficient to assume existing technologies.)
 - Nb₃Sn TF coils (if required)
 - Nonconducting structural materials for superconducting (s/c) PFC (if s/c is used)
 - Active impurity control technology (if passive techniques are inadequate)
 - High power negative ion source } (if >200-keV beams are needed)
 - 300-keV NB switch tube }
 - High velocity pellet injection (if pellet fueling is necessary and 2000 meters per sec is inadequate)
- Two programs have critical timing questions in the generally compressed project schedule and must be closely examined further.
 - NbTi TF coils (questions of prototyping, manufacturing, and assembly contingent upon technology development and engineering)
 - Pellet fuel injector (need is principally contingent upon physics information; given that, questions of developing backup techniques are contingent upon both physics and technology)

On the third point — implementation — development of a comprehensive Work Breakdown Structure, a master schedule based on the Work Breakdown Structure, and a first draft of the ingredients of the program plan is being treated in Part IV, Program Planning.

REFERENCE FOR ABSTRACT

1. R. V. Jenson, D. E. Post, et al., *Calculations of Impurity Radiation and Its Effects on Tokamak Experiments*, PPPL-1334 (March 1977).

1. INTRODUCTORY SUMMARY

1.1 Introduction

This specific, fundamental part of the TNS Program Plan has its roots in all the earlier advanced studies, especially the EPR studies,¹ but has become of intense interest most recently. In the ORNL Form 189 Program Proposal,² in the transmittal from ERDA-ORO to UCC-ND about line items,³ and in the specific request made by ERDA-DMFE,⁴ a growing awareness of the importance of R&D program planning and needs assessment has been made clear. The R&D assessment has been divided into two complementary pieces: one oriented toward the necessary research and general development that describe the base from which a design must start and upon which it must build; another oriented toward the design specific R&D that describes the extent of the work that must be completed during the design process. This Part presents the former, and Part III the latter.

In this Part, the assessment method is presented in Sect. 2, the findings in the plasma physics area in Sect. 3, and the findings in the hardware-oriented work breakdown structure (WBS) system in Sect. 4.

1.2 Summary of Findings

Three different facets of the research, development, and demonstration needs comprise the whole, namely:

- Generic and specific fusion physics questions such as:
 - How will plasma transport scale with collisionality?
 - How many volts and voltseconds will TNS need?
- Generic technology questions such as:
 - Will fabrication of large-scale superconducting TF coils be demonstrated by the time of TNS device cost estimate?
- Specific engineering questions such as:
 - What is a viable technique for repair or replacement of the innermost PF windings?

In the three sections that follow, each of these facets is treated in turn.

1.2.1 Fusion physics situation as applied to TNS

Supporting information for this summary is found in Sect. 3. Three tangible outputs are presented there.

- Development of the questions that should and can be answered in each major area at the various phases of the design process.
- An evolutionary development (listing) of the physics issues requiring further study and an indication of facility availability.
- A discussion of the specific TNS physics needs.

Our analysis of (1) the base from which to ask the questions, (2) the ability to address the questions, and (3) the projected timeliness of the answers is presented in the following paragraphs.

1.2.1.1 Base from which to ask questions. The adequacy of a base in this fundamental and complex area — fusion physics — can be measured in two complementary ways.

- Pragmatic achievement (plasma parameter values attained)
- Fundamental understanding (ability to predict extrapolations with confidence)

With respect to achievement, four numbers are usually quoted:

1. plasma density N ,
2. energy confinement time τ ,
3. plasma temperature T , and
4. effective impurity level Z_{eff} .

Even though these parameters are a simplification of the real situation characterized more by plasma regimes, profiles, transients, etc., they still represent quantifiable and recognizable measures of success.

Taken in the usual combination, the average values needed for an ignition demonstration in the TNS plasma are

$$\left. \begin{array}{l} N\tau \sim 2 \times 10^{20} \text{ sec/m}^3, \\ T \sim 10 \text{ keV}, \\ Z_{\text{eff}} \sim \leq 1.5. \end{array} \right\} \text{ TNS}$$

(The Z_{eff} measure does not yet reflect the serious impact of very small amounts of high Z impurity). At the initiation of the tokamak studies — late 1960s — the values were

$$\left. \begin{array}{l} N\tau \sim 10^{17} \text{ sec/m}^3 , \\ T \sim 0.5 \text{ keV} , \\ Z_{\text{eff}} \sim 3-10 \gg 1 . \end{array} \right\} \text{T-3 (USSR)}$$

By the early 1970s, these values had been improved to

$$\begin{array}{ll} N\tau \sim 10^{18} \text{ sec/m}^3 , & \text{ORMAK (ORNL)} \\ T \sim 1 \text{ keV} , & \text{ST (PPPL)} \\ Z_{\text{eff}} > 1 . & \text{TFR (France)} \end{array}$$

Within the last couple of years, significant improvements have resulted in

$$\begin{array}{ll} N\tau \sim 2 \times 10^{19} \text{ sec/m}^3 , & \text{Alcator (MIT)} \\ T \sim 1.8 \text{ keV} , & \text{ORMAK (ORNL), TFR (France)} \\ Z_{\text{eff}} \sim 1 . & \text{Alcator (MIT)} \end{array}$$

Although the experimental regimes in ORMAK and Alcator are characterized by many parameters in addition to the four quoted above, there are some important points in common ($Z_{\text{eff}} \sim 1/N_e$ and $\tau_E \sim N_e/Z_{\text{eff}}^{1/2}$ in specific situations). If it becomes possible through improved, detailed understanding to consider the two experiments as complementary parts of a generic tokamak, then even greater improvements can be inferred.

In the commonly used measure of remaining distance to success,

$$\frac{(N\tau T) \text{ TNS}}{(N\tau T) \text{ at any given time}} ,$$

progress is clear and satisfying as seen by the change in this quotient over the years:

$\sim 10^6$ in early 1960s (mirrors and theta pinches) ,

$\sim 2 \times 10^4$ in late 1960s ,

$\sim 2 \times 10^3$ in early 1970s ,

$\sim 4 \times 10^2$ today in Alcator , and

using the generic tokamak concept, $\sim 10^2$ in Alcator and ORMAK taken together.

With respect to understanding or the ability to predict extrapolation with confidence, Table 1 can serve to focus the discussion.

The end point of the "understanding" process is the ability to provide definite criteria for reactor designers. A convenient starting point is the physics assessment made in WASH-1295 in 1973. At that time, plasma confinement and heating were the dominant issues treated in a list of four major headings subdivided into seven generic problems. The entries in column one, headed WASH-1295, represented the first step toward the end point referred to above; this first step was a basic physics approach to the fusion reactor considered in the abstract.

As the program began to focus on a class of reactors, EPR, another step was taken. This second step, EPR RD&D shown in column 2, represents a more detailed and comprehensive approach to the problem, but one still oriented from a basic physics viewpoint. In this column, the "new" issues listed involve getting to ignition and to burning after ignition is achieved.

In the present and third step in this process, the questions that must be answered for a specific device, TNS, become the framework for discussion of the physics issues. In this view (column 3), eight discharge-cycle-oriented design areas are identified, and within them about 30 specific areas in which more knowledge is necessary are separately dealt with in Sect. 3.

In the fourth and next step in the process, the discharge-cycle-oriented physics problems become reordered to match the design-oriented arrangement. Shown in the column headed "primary design inputs" are the four principal design areas (A-D) requiring intimate involvement with the basic physics issues. Under each design area are shown the essential

Table 1. Evolution of physics problems from abstract to specific design inputs

Early development				Present development			
Basic physics approach (in the abstract) WASH-1295 1973		Detailed basic physics approach (in the abstract) EPR RD&D ^a 1976		TNS-oriented framework (applied to specific design requirement) TNS RD&D ^b 1977			
Goals (G), Problems (P), Topics (T)		EPR Problem areas		Discharge-cycle oriented TNS No.		Design-oriented	
		EPR RD&D No.	Title	TNS RD&E No.		Primary design inputs A-D from TNS No.	Secondary design inputs WBS No.
I. Confinement and heating in plasma physics regime (G)							
A. Configurational stability (P)							
1. MHD ^d equilibrium (T)	→	A-1	Macroscopic equilibrium	→ 3	1. Establishing the current (1.2 Wall-plasma interaction) ^c		
2. MHD stability (T)	→	A-2	Macroscopic stability	→ 3	2. Heating to ignition	PFS - magnetics and plasma shaping (A) 1,3	Electrical 23, 24 (A-D)
B. Plasma transport and scaling (P)					(2.4 Heating profiles, wall loadings in n/c plasmas)		
1. Microscopic plasma transport (T)	→	A-3	Plasma transport	→ 3			
2. Scaling laws (T)							
C. Heating (P)							
1. Heating (T)	→	A-4	Plasma heating	→ 2	3. Maintenance of discharge during burn phase	Heating (B) 1.2, 2	
D. Boundary effects (P)							
1. Impurity control (T)	→	A-5	Impurity control	→ 7			Mechanical 22, 24 (A-D)
2. Plasma material interactions (T)	→	A-6	Plasma edge	→ 7			
II. Burn for net energy gain (G)							
→	{	A-7	Fueling	→ 6	4. Removal of heat	TF (C) 2, 3, 4, 7	
		A-8	Plasma dynamics				
			Start-up	→ 1			Support 25 (A-D)
			Burn control	→ 3-6	5. Ash removal		
			Shutdown	→ 8			
III. Other (G)							
→	{	A-9	Diagnostics		6. Particle replacement	Particle control (D) 1.2, 2.4, 5, 6, 7, 8	IC&D 26 (A-D)
		A-10	Atomic and molecular cross sections		7. Prevention of impurity buildup		
					8. Shutdown procedure		

^aM. Roberts et al., *Oak Ridge Experimental Power Reactor Study. Part 6: RD&D Needs*, ORNL/TM-5577 (January 1977).^bThis document.^cSee Table 3 in Part II for complete listing of detailed areas (1.1-1.3, 2.1-2.5, etc.).^dMagnetohydrodynamic.

contributing discharge-cycle-oriented issues from column 3. In the column headed "secondary design inputs," the major elements of the device portion of the WBS are displayed. Each of these four elements receives its input from each of the four primary-design input areas (A-D).

Through the transitions between each of the columns going from left to right, from abstract to specific, the basic physics issues can be coupled into the design requirements for each specific WBS system.

In addition to the basic fact that we can now begin to define specific design-oriented experimental questions that need to be addressed, the following brief discussion presents an attempt to establish a measure of understanding.

Each of the eight design-oriented issues is being addressed to some degree on a theoretical level. The component parts vary in their status: some such as "transport" are topics of long-standing investigations; others such as "start-up" and "rapid heating to high β " are newly under way; and others such as "impurity control," which are characterized by a paucity of real understanding, are topics of common interest everywhere.

On the experimental level, the situation differs somewhat. Each issue is being faced by necessity but in different ways. "Start-up" and "shutdown" are characterized more by empirical procedure than by systematic understanding, but heating and transport are being systematically studied (Table 2).

SUMMARY: Each topic is being investigated theoretically at some level. Some crucial experimental studies are not yet under way. The real impact of the theoretical and experimental program uncertainties comes in dealing with the second problem, the ability to address the necessary issues in the near-term future.

1.2.1.2 Ability to address these questions. Will the fusion program continue the activities now being systematically investigated so that they apply to regimes of direct TNS relevance? In general, the answer is yes, with one significant question. Given the names of the fusion physics problems as in Table 1, we can now consider the requirements for solutions. A strong theoretical and computational framework

Table 2. A measure of physics understanding -- current work in progress

Essential design topics (discharge-cycle orientation from Table 1)	Theoretical studies		Experimental work	
	Longstanding	Newly under way	Empirically based	Systematically investigated
1. Establishing the current (start-up)		V ^a	V	X ^b
2. Heating to ignition		V	V	V
3. Maintenance of discharge during burn phase				
• configuration	V		V	X
• beta		V	V	X
• poloidal field systems		V	V	X
• scaling	V		V	V
4. Removal of heat				
5. Ash removal				
6. Particle replacement	V		V	X
7. Prevention of impurity buildup	V		V	X
8. Shutdown procedure		V	V	X

^aV indicates specific topic being investigated.

^bX indicates current lack of experimental or theoretical work.

is a basic ingredient for solutions. There is, however, a clear lack of fundamental understanding in the area of the TNS operating regime. There are no experiments in the low collisionality regime ($v^* \sim 0.01$) that can serve as guides for selection of this theory. Experiments (PLT, PDX, ISX) in the near future will be addressing these questions so that a complementary theory and diagnostics program must be assured to make use of this experimental information.

Higher temperature and larger sizes can be obtained in even more applicable regimes in the Princeton Large Torus (PLT) and TFTR.

Does the fusion program plan to initiate those activities in Table 2 listed as being now lacking? The answer here is mixed, as shown in Table 3. The many "yes" entries in Table 3 testify to the fact that the hardware exists in most instances to do the job and that plans also exist in most cases. There is an important distinction that must be made, however, between "plans" and "program commitment." Until each area is the object of an actual program commitment with assigned budgets and milestones representing an institutional commitment, then the "yeses" are incomplete. An evaluation of the actual commitments was not done here systematically.

SUMMARY: The fusion program in its near-term plan does have the ability to address the necessary questions with an ever increasing capability with two principal groups of exceptions.

1. There is no facility presently planned that is able to investigate configuration maintenance and then optimization at high β and temperature with a real-time active feedback, poloidal field system. Configuration development and MHD stability can be studied in planned facilities, as can the maintenance of circular, beam heated plasmas. Configuration maintenance or the evolution of beam heated, high- β , noncircular cross section plasma equilibria is not now covered in the plan.
2. There must be a stronger applied effort in impurity dynamics, plasma transport, and, most critically, in coupled equilibrium, stability transport, and heating simulation of ignition scenarios.

Associated with the fulfillment of these specific theory efforts is the probable need for additional computing facilities.

Table 3. A measure of the ability to address the TNS questions in the planned experimental program

Essential design topics	Systematically being studied now?	Possible in next generation of experiments ^{a,b?} (1977-1978)	Possible in succeeding generations ^{a,b?} (1979-1980)	Possible in final experiments ^{a,b,c?} (1981-1982)
Start-up	Started	Yes— ^d	Yes—	Yes—
Heating	Yes	Yes	Yes	Yes
Maintenance of discharge				
Configuration (ohmically heated)				
Circular	Done to 0.5 sec			
Elliptical (+D)	Started	Yes	Yes	Yes
Doublet	Started ^e	Yes	Yes	Yes
Beta (beam heated)	Started ^f	Yes	Yes	Yes
		but need configuration maintenance (many seconds), optimization, and collisionless studies		
Scaling	Yes	Yes	Yes	Yes
Fueling	Started	Yes	Yes	Yes
		(if pellet development is successful)		
Impurity control	Started	Yes	Yes	Yes
Shutdown	Equipment available, but no plans			

^a Assumes capability exists with minor modifications and without regard to experimental schedules, i.e., how many simultaneous experiments can be conducted.

^b Assumes about one year from time of initiation of operation to first meaningful results.

^c Assumes this is last input to basic TNS design, which is at this time in the detailed drawing-construction phase. Continuing information will affect operational procedure and, of course, if necessary alter even completed detailed design or fabrication.

^d Yes = hardware + plans. Yes- = hardware but no plans. "Plans" is not equivalent automatically to a funded, committed program with milestones incorporated as a format element in the DMFE program.

^e Have 15% of flux outside separatrix for 15 msec; need 40% for ~1 msec.

^f Through 1%; need 5 to 10%.

1.2.1.3 Timeliness of the answers. Whether or not the planned physics program is "timely" depends upon the schedule against which "timeliness" is being measured and upon what kinds of outputs are expected. A detailed development of both sides of this question now is not meaningful because of uncertainties in both areas. What can be done, however, lends credence to the thesis that the physics program can provide timely input.

The design process for TNS goes in stages from considerable uncertainty to minimum uncertainty. So does the physics understanding process. Do the two match in large measure? As outlined in Table 4, yes, they do.

1.2.1.4 Summary of physics findings. A physics basis composed of achievements in plasma parameters, considerable operational understanding, and a broadly based and applied program of theoretical support does exist from which to begin the first steps of the TNS design process. These first steps require the ability to define ranges of expected design parameter values; subsequent steps in later years require more specific inputs.

The ability to address the relevant, essential questions in the near-term does exist with two significant exceptions.

- There must be a configuration maintenance, high- β and high temperature, actively controlled plasma facility capable of providing answers in this central plasma regime expected for TNS operation.
- There must be a stronger applied theoretical program in impurity dynamics, plasma transport, and, most critically, in coupled equilibrium, stability, transport, and heating simulation of ignition scenarios. With such a program our present, incomplete knowledge of magnetized plasma (and impurity) transport and heating can be sufficiently improved to support fusion development over the next decade.

The physics program outputs, both experimental and theoretical, can be timely as well as can be understood now with the uncertainties that exist in both the TNS scheduling and the physics program.

Table 4. Elementary integration of design and physics understanding time scales^a

Fiscal year	1976	•	1977	•	1978	•	1979	•	1980	•	1981	•	1982
<u>Design stages</u>													
Facility			PCD & CD ^b		Advanced eng.		Prelim. Detailed eng. & construction						
Scoping studies													
Device			Device envelope		PCD feasibility study		Conceptual design		Advanced eng.		Prelim. Detailed eng.		
<u>Levels of information</u>													
			Initial (Ranges)				Preliminary (Techniques)					Final (Detailed data)	
<u>Physics stages</u>													
Basic achievements and identification of issues			First focused studies on special topics — preliminary choices of heating energies, start-up scenarios, etc.				Investigation of basic assumptions at high β , low Z; specify techniques with confidence					Verification and quantification of expectations in large size and low Z, high T	
			PLT-beams, ISX				PDX, ISX-U, D-III					TFTR(H), PDX-U	

^aPotential impacts on schedules of the February 1977 budget reductions are not yet considered here.

^bPreliminary conceptual design and conceptual design.

1.2.2 Fusion technology situation as applied to TNS

The starting point for the technology discussion is the hardware-oriented Work Breakdown Structure (WBS). The device hardware portion is shown in Fig. 1. The full WBS is discussed more completely in Part IV.

Table 5 outlines the relevant base program for each system, whether planned programs will address necessary questions, and whether this is done on a timely basis.

Each of the technology areas is addressed specifically with a prose summary and a schedule comparing development to design schedule in Sect. 4.

SUMMARY: With a few exceptions, base programs exist in each area, planned programs are addressing the issues, and these planned programs, to the degree that such a judgment can be made at this time, do appear to be timely. The exceptions are in the toroidal field coils, impurity and particle control, energy conversion, main vacuum pumping, and central C&I systems as discussed in the footnotes to Table 5 and summarized in Table 6.

Fig. 1. The device hardware portion of the WBS with identifying numbers.

Table 5a. Tokamak systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
22a	Toroidal vacuum vessel	V ^a	V	V	TFTR, industry
22b	Machine structure	V	V	V	TFTR, industry
22c	Toroidal field coils	V ^b	V ^b	? ^{b,c}	ORNL/LCP ^d /SCMDP, ^e industry
22d	Poloidal field coils	V ^f	V ^f	V ^f	PDX, ^g TFTR
22e	Shielding	V	V	V	ORNL/Integral Expt.
22f	Impurity control	X ^h			
22g	Tokamak systems mockup	V	V	V	TFTR, JET, ⁱ industry

^aThroughout Table 5, V indicates specific topic being investigated, and X indicates current lack of experimental work.

^bAssumes NbTi s/c is required and adequate. If Nb₃Sn s/c coils are required, then a minimum of one additional year is added.

^cThe role of a full-size prototype and the method of integrating coil tests with design schedule in this critical path item are not yet fully clear.

^dLarge Coil Program.

^eSuperconducting Magnet Development Program.

^fAssumes normal PF coils. If s/c coils are required, then a nonconducting structural material must be used, perhaps incurring delays.

^gPoloidal Divertor Experiment.

^hIf more extrapolation of Alcator experience can be made to TNS plasma regime, then no vastly new technology base is required. If this is not possible, then some new technology such as that associated with divertors will be required. In any case, a study of limiter material technology requirements is necessary.

ⁱJoint European Tokamak.

Table 5b. Electric power and control systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
23a	Primary energy	V ^a			Industry, TFTR
23b	Primary and secondary distribution	V ^a			Industry
23c	Energy conversion	V	X ^b		Beam Prog., TFTR industry
23d	Standby or emergency	V ^a			Industry

^a cursory examination of these areas indicates no development requirements; further investigation is deferred at this time.

^b Existing motor generator flywheel (M-G-F) sets along with solid-state devices and mechanical switches can satisfy the TNS needs, but potentially at prohibitively high costs. Associated with the cost issue is the development question of multiple ganging of solid-state devices. If circuit analyses indicate substantial cost savings in the solid-state switches (the dominant cost item) through use of homopolar machines, then the homopolar generator development program should be pursued vigorously for economic reasons.

Table 5c. Plasma heating systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
24a	Neutral beam heating system	V	X ^{a,b}		TFTR-ORNL
24b	RF heating systems	V	X ^c		PLT, ISX, EBT, ^d industry

^aTwo TNS requirements beyond TFTR beams must be addressed:

1. increasing ion source and switch tube pulse length capacity to about 10 sec from the present value of about 1 sec;
2. increasing the power per unit beam line to permit about 75 MW(e) to be physically accessed in the TNS device.

^bIf the decision is made to require neutral beams in the 300 keV range, then two additional requirements must be met:

1. development of a high power negative ion source;
2. development of switch tubes capable of 300 keV — present tubes are already put in series to reach 150 keV.

^cRF heating experiments at electron cyclotron resonant heating (ECRH) regimes provide a confident base of extrapolation in physics but not in technology. Present judgment is that it is not possible to develop high power ECRH tubes suitable for bulk heating by TNS schedule. Supplementary or complementary heating does seem reasonable, and an adequate supply of modest power, high frequency tubes could be available if microwave tube programs are supported at the present levels. At lower frequencies, there is less certainty over the effectiveness of ion cyclotron resonant heating (ICRH) or lower hybrid heating (LHH), but experiments are planned for PLT in the next two years. Preparation should be made to accelerate the RF program to such a level that if negative impurity control information comes from PDX (thereby making it more difficult to heat with beams), large-scale RF heating at frequencies below ECRH can be made possible.

^dElmo Bumpy Torus.

Table 5d. Tokamak support systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
25a	Remote servicing	V	V	V	TFTR, JET industry
25b	Fuel handling	V	V	V	TSTA
25c	Main vacuum pumping	X ^a			
25d	Heat removal and cryogenics	V	V	V	LCP, Fermi Lab.
25e	Experimental area ventilation	V			Industry, TFTR
25f	Radioactive waste handling	V			Fission
25g	Fuel injector	V	V	? ^b	ORNL, Univ. of Illinois

^aCompound gas pumping of helium and hydrogen isotopes has been identified and demonstrated by ORNL as a problem with commercially available cryo panels. Development work is needed here to support full-scale demonstration in TSTA.

^bThe timeliness of the fuel injector is questionable because of the uncertainty in physics requirements. If pellets are required and velocities of <3000 meters per sec are adequate, then the program is timely. If >3000 meters per sec velocities are required or other, high technology solutions are required, then timeliness is in doubt.

Table 5e. Instrument, control and data systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
26a	Central C&I	V	X ^{a,b}		All expts. CSD Lab. ^c
26b	Operations instrumentation	V	X ^{a,b}		
26c	Scientific instrumentation	V	X ^{a,b}		

^a A principal gap is plasma configuration sensing and control. As plasma pulse times become longer, active real-time feedback will be necessary. As importantly, the controlled plasma is expected to be a high- β , shaped plasma, which is not yet in hand. An important need, therefore, is experimental work with an actively controlled, shaped, rapidly heated plasma.

^b A second principal gap is control of abnormal discharges, which becomes important as the energy content of the plasma increases and the repair time lengthens. Specific attention directed to this area along with shutdown experiments is called for.

^c C. S. Draper Laboratory.

Table 6. Main gaps in the fusion technology program for TNS

Topic	New program commitment needed ^a		Focused study required	Uncertain criteria could require new or increased program	Timing unclear ^b
	Technically	Economically			
NbTi TF coils					V ^c
Nb ₃ Sn TF coils				V	
S/c PFC structural material				V	
Impurity control technology				V	
Limiter materials			V		
PF electrical systems		V			
NB switch tube and ion source pulse lengthening	V				
NB power per unit source	V				
High power negative ion source				V	
300-keV NE switch tube				V	
Compound gas pumps	V				
High velocity pellet injection				V	V
Plasma configuration sensing and control	V		V		
Abnormal operations control	V		V		

^aIn each case, the capability to proceed toward solution exists: the gap is in commitment, not capability.

^bApplies to those technologies assumed to be leading candidates for TNS (e.g., NbTi, positive ion beams, etc.). If design decisions require any of the six advanced technology programs shown in the column to the left, then those programs will show as "timing unclear" also.

^cV indicates specific topic being investigated.

REFERENCES FOR SECTION 1

1. *Oak Ridge Tokamak Experimental Power Reactor Study*, Parts 1-6, ORNL/TM-5572-5577.
2. Program and Budget Proposal Form 189; see Part IV, Appendix.
3. December 7, 1976, letter from R. Hart to R. F. Hibbs; see Part IV, Appendix.
4. January 10, 1977, letter from J. M. Williams to J. F. Clarke; see Part IV, Appendix.

2. METHOD OF ACCOMPLISHMENT

2.1 Philosophy of Focus

The theme followed in this activity was to focus on the end product — TNS in mid-to-late 1980s — using the minimum number of steps. Specifically, this focus meant asking questions related to a specific range of design parameters achievable in a fixed, brief period of years between today and various TNS design stages. Therefore, rather than providing a program in which all questions are answered (i.e., in which all design options are uniformly investigated and evaluated), we focus on an aggressive, higher risk program in which the achievement rate in selected areas is made as high as is credible.

Examples of this philosophy are to be found in discussions of the TF coils, neutral beams, fuel injection, and plasma heating in general. In each area, the plan is based upon aggressive pursuit of one principal, near-term technology with lower level backup programs carried for possible expansion when necessary. This plan was judged necessary for this draft evaluation because of limited resources available (time and personnel) during the study.

In this schedule-oriented exercise, the following choices were made reflecting our view of which technologies would be available first. In the basic technical studies forming the major task of the TNS Program, a thorough investigation of the various options is being made; this larger study, on which our technology choices will be based, is now under way but has not been completed and is not represented by these schedule-driven choices.

	<u>Principal</u>	<u>Lower level backup</u>
TF coils	NbTi	Nb ₃ Sn
Neutral beams	Positive ions (150-keV)	Negative ions (300-keV)
Fuel injection	Pellets	Others
Heating	Beams	RF
PF coils	Copper	NbTi
Energy conversion	Motor-generator sets	Homopolar machines

2.2 Questions Asked at the Initiation of this Study

2.2.1 Is there a base (in the U.S.) from which to start?

In both physics and technology (for each WBS system criteria area), consider these four elements of the base:

- Knowledge
 - Do we know the problems?
 - Can we delimit the possible range of solutions?
 - Can we postulate the probability of various answers?
 - Can we project a way to resolve questions?
- People
 - Do we have a critical mass in each relevant area now?
 - Could they be assembled now?
- Facilities
 - Do we have appropriate facilities (devices, codes, computers) now?
 - Will planned facilities be adequate?
- Operating Funds
 - Are there sufficient funds in planned budgets for FY 1977 and FY 1978 to get started?

2.2.2 Does the "right" program exist?

In both physics and technology (for each WBS system criteria area), consider these four elements of the program:

- Requirements
 - Do we know the criteria and/or needs?
 - Is our listing of RD&D needs adequate?
 - Label key tasks on summary sheets (tasks, facility, timing, cost, judgment of applicability).
- Priority
 - Are tasks in proper priority compared with needs assessments from EPR and TNS?
- Timing
 - Are programs paced properly to match TNS schedule?
 - Can we iterate between physics and technology?
- Coordination
 - Are objectives really common between TNS and support programs?

2.2.3 What is required to focus on TNS?

In both physics and technology, consider these three factors:

- Redirection
 - Which programs need to be redirected?
 - How great is this redirection for which pieces of the program?
 - What stands in the way of this redirection?
- Reorganization
 - To what?
 - What is required to accomplish it?
- Increased Funding
 - After condensation and redirection of existing funds, how much additional funding would be needed, and when?

2.2.4 Reevaluation of the questions

The questions listed above were asked at the outset of the intensive study. As the work evolved, better, more direct ways were found to match the available information sources with the needs within the given time period. These more direct ways are illustrated by the charts and discussions in this Part, Sects. 3 and 4. After a number of attempts to tie the physics, technology, and engineering pieces closer together, we quickly learned that these fusion fields do not yet lend themselves to an integrated presentation. As a result, the physics discussion, Sect. 3, is principally presented as a self-consistent description of the closely interleaved research problems. However, the technology and engineering discussions, Sect. 4, are focused on a master WBS and schedule, but need to be tempered by the recognition that conceptual design has not yet begun. Our ongoing work in this area is aimed at improving the integration and providing answers to these questions.

2.3 Methods Used to Investigate the R&D Needs Issue

The status of the overall fusion physics, technology, and engineering plan is extraordinarily difficult to assess in a simple, direct manner, especially in a short time period. As a result, we have chosen

to take various "slices" through this multidimensional space that characterizes the complex fusion program and to represent the important aspects clearly in a stepwise fashion. Figure 2 illustrates this process of stepwise representation.

The first "slice" is through the physics part and is presented in Table 1 as an evolution of the physics approach to TNS; this evolutionary listing is both time independent and independent of specific experiments. Under "early development," Table 1 shows the evolution from the general abstract (i.e., related primarily to plasma physics as opposed to operating discharge or machine design) view in WASH-1295 to the more detailed but still abstract view in the ORNL-EPR RD&D needs document.¹ Under "present development," Table 1 takes these same concerns and reorders them to a discharge-cycle orientation^{*} shown as TNS RD&D; the EPR numbers are shown for conversion from abstract to specific. In the far right columns of Table 1, the most recent evolutionary step — conversion to design-oriented ordering[†] — is shown. The four functional elements listed as primary design inputs[‡] are intimately connected to the discharge cycle. The hardware-oriented secondary design inputs[§] are, in turn, dependent upon the criteria developed from the four primary design systems. Through these last conversions, it is possible to understand the steps in the complex process of relating work on abstract physics problems to design-specific data requirements.

^{*}This "discharge-cycle orientation," suggested by G. G. Kelley, is intended to provide a systematic approach to studying the plasma as an element in the overall system.

[†]"Design-oriented ordering" provides a systematic approach to studying the plasma characteristics as they impact each design element of the tokamak device (WBS level 2).

[‡]"Primary design inputs" represent a convenient intermediate step between the plasma as an element (discharge-cycle orientation) and the engineering design elements of the whole system (secondary design inputs). This breakdown into four major areas is the result of an attempt to find an "orthogonal" set of major plasma/design themes that bridge this difficult gap.

[§]"Secondary design inputs" represent the end point in the design evolution — the breakdown of the device into the WBS elements which can be grouped reasonably well into the traditional engineering disciplines.

Fig. 2. A stepwise approach to the representation of the multi-dimensional design space.

With this first "slice" in mind, one can now add dependence upon calendar time and experiments. In Sect. 3, Table 7 starts with the discharge-cycle orientation and lays out the information requirements over the next five years corresponding to the design schedule. Table 8 then expands Table 1 by including the detailed areas in which more knowledge is necessary, probable experiment testing places, and priorities.

Starting now from the technology side, a typical first "slice" through the R&D needs is shown in Fig. 3, taken from the complete set of data in Part III. This hardware-oriented slice is ordered by WBS systems and is tied to the project schedule rather than to any calendar year. Figure 3 lists by example all the important characteristics of each R&D need.

With the first hardware-oriented "slice" in mind, one can now add dependence on calendar time and experiments by using the WBS system program plan charts, Figs. 5-13 and 15-21, contained in Sect. 4. These charts incorporate the design-specific R&D needs shown in Fig. 3, plus the required schedule and associated R&D programs.

The next iteration of this work will try to incorporate these two different "slices" into one coherent picture.

REFERENCE FOR SECTION 2

1. M. Roberts et al., *Oak Ridge Tokamak Experimental Power Reactor Study. Part 6: RD&D Needs*, ORNL/TM-5577 (January 1977).

Date: 2/8/77By: R. J. GromadaItem: 1.3-2Priority: 2SYSTEM: Poloidal Coil AssemblyCOMPONENT: InsulationTOPIC: Evaluation of Radiation Damage to Electrical Insulation for Copper Coils

PROBLEM: The copper shaping field (SF) coils for TNS are located within the bore of the toroidal field (TF) coil array, an area subjected to high radiation fluxes. The location of each coil, relative to the plasma center, will ultimately be determined by magnetic field studies. The maximum neutron dose on the coils nearest the plasma is expected to reach 2.0×10^{11} rad.

The electrical insulation on the coils will have to withstand the radiation without substantial loss of mechanical or electrical properties. The best radiation-resistant insulations (epoxy resins) currently available are able to withstand a dose of only 10^{10} rad without damage and may not be suitable for use in TNS. Any repair or replacement of the coils due to radiation damage would be difficult and expensive, and would interrupt the normal operation of the machine. It is, therefore, essential that a number of the more promising coil insulations be tested to insure their suitability (radiation resistance) for use in TNS.

DATA REQUIRED: Tests performed should determine the mechanical properties (bond strength, impact strength, and tensile strength) as a function of absorbed radiation, and the electrical properties (resistivity and dielectric strength) as a function of absorbed radiation dose. Candidate insulating materials tested should include glass-fiber-reinforced, mica-filled epoxies, blended epoxies, and fine-grained (0.5 to 1 micron) epoxy fillers.

SCOPE OF TASK:

- Design and fabricate test hardware capable of performing radiation tests on candidate insulating materials.
- Prepare test samples from coil materials using manufacturing techniques typical of coil installation.
- Perform tests at a suitable irradiation facility.
- Determine the electrical and mechanical properties of the test materials for various radiation doses.

SCHEDULE NEED/IMPACT: Prior to end of Title I design.

RESOURCE REQUIREMENTS: Sophisticated radiation test facility, engineering mechanics test laboratory.

AVAILABLE RESOURCES/PROGRAMS: National laboratory (FFTF, RTNS, HFIR) facility.

ESTIMATED COST: \$200,000

ALTERNATIVES: Without the material test data, coil design would have to depend on the extrapolation of existing insulation properties after irradiation. This implies considerable uncertainty in effective machine lifetime and uncertainty as to EPR "stretch" capability.

Fig. 3. A typical TNS project-specific RD&D assessment.

3. PHYSICS RESEARCH AND DEVELOPMENT ASSESSMENT

Both the technological design and the operating goals of TNS are based upon the physics of the reacting plasma. It is appropriate and necessary to review briefly the results of the plasma physics program which are relevant to TNS and thus identify those areas in which future efforts should be concentrated.

In our development of the physics base for TNS, we will concentrate only upon those areas required for TNS operation. In doing so, we will narrow our purview even further by making informed (but often arbitrary) choices of technology for TNS. For example, we feel that neutral beam injection is the most proven heating method, and we emphasize and deemphasize various areas of physics accordingly.

However, many topics not needed for TNS and hence not discussed here may be vital for future generations of machines leading to commercial feasibility.

To assess completely and properly the relevance of the physics program to TNS would be a monumental and very difficult task. What we have done in the limited time allocated for this study is to make a set of informed judgments which we present here.

In Sect. 3.1.1, we discuss the impact that physics inputs have on the technological design of TNS. Next, in Sect. 3.1.2, we review the present state of physics knowledge in the framework of the eight parts of the discharge cycle and identify the information needs. In Sect. 3.1.3, we identify a particular model for TNS operation and from it derive a schedule of physics needs in Sect. 3.1.4. Table 8 serves as a summary of this chapter.

Section 3.2 expands on the specific questions and needs for supporting R&D associated with the primary design input areas, starting at this time with the poloidal field system, including poloidal magnetics and plasma shaping.

3.1 The Physics Questions

The broad objectives of TNS are clear. The device must burn deuterium-tritium (D-T) and must demonstrate ignition. These objectives

have a sound basis, both politically and scientifically. Funding in the billion dollar range must be justified by an easily understood, large step toward controlled fusion power. Ignition is such a step and, in fact, is the important next step. Furthermore, since large experiments will be producing information before TNS begins to operate, TNS must be able to give answers in areas not already planned for investigation. Without a fusion power source deep in the plasma, a device large enough to satisfy this requirement probably could not be heated satisfactorily.

Specific decisions concerning the design choices for TNS are more difficult. A start at providing a framework for dealing with these design choices is presented below.

3.1.1 The impact of physics on TNS technology requirements

A major class of decisions is those which affect the physical characteristics of TNS. Simply stated, physics input and plasma engineering decisions are required to design the machine. The machine designer must know answers to the following questions:

1. How large should the device be? How strong should the magnetic fields be? How much auxiliary heating should be provided? These questions are listed together because they involve trade-offs.

Answers require information on

- a. energy transport,
- b. heating technology,
- c. the choice of β limit and q limit,
- d. the effect of plasma shape, and
- e. impurity buildup.

2. Should there be a divertor? What could it be expected to do?

The answers require information on

- a. particle transport throughout the plasma,
- b. particle input deposition profiles, and
- c. the physics of the wall-halo-edge plasma interactions.

3. What are the volt-second requirements? The answer depends on

- a. the physics of the breakdown phase,
- b. loop voltage during the ignition and burn phases, and
- c. desired length of burn.

4. What kind of OH-vertical field configuration should be provided.

Information is required on

- a. the expected beta,
- b. the plasma shape desired,
- c. the engineering difficulty and cost aspects of the distance of the windings from the plasma,
- d. the need for magnetic shielding of the TF coils, and
- e. the air core, iron core trade-offs.

3.1.2 The physics basis for TNS design

The next level of decision requirements deals with the information called for in the listing above. Such information can come from physics and technology.

The physics considerations will be dealt with in this section. They involve (1) the present state of our knowledge, (2) the assumptions that must be made to proceed in spite of a lack of knowledge in some areas, (3) the depth to which it is fruitful to pursue analytical and computational models, and (4) the possible redirection of presently planned experimental work. They will be dealt with in terms of the major problems. It must be remembered that underlying all other assumptions are the energy and particle transport properties, many aspects of which are not known.

In a framework oriented to the discharge cycle (Table 7), the physics problems are:

1. Establishing the current. We know:
 - a. Rather large devices (PLT, T-10) establish acceptable current distribution with simple procedures.
 - b. Impurities are brought into the plasma during breakdown with normal procedures (DITE).
 - c. The major radius of discharges can be controlled to keep the plasma centered in the chamber (many experiments) or grossly moved for compression (ATC).

We need more information on:

- a. The volt-second breakdown requirements in a large plasma. These can come from studies in PLT and from computational models.
- b. The wall-plasma interaction during breakdown and the possible usefulness of various procedures for reducing built-in impurities. Specifically, we need to know whether it is

possible to prevent wall-plasma particle interchange during breakdown; if not, we need to know how to minimize impurity influx. Also, we need to know how much residual impurity concentration must be planned for. This information can come from model studies in the Impurity Study Experiment (ISX), and perhaps from Poloidal Divertor Experiment (PDX). The first order of business would seem to be to deal with the simple fact that containment is extremely poor until a rotational transform is established; hence, any diversion of the surface of the plasma to a hidden dump would be in competition with rapid flow of ion pairs to the chamber wall. This question could be attacked by computational means and by scraper and probe studies in a device like ISX. Plasma properties in the shadow of the scraper would imply the desired information. Information from Pulsator may be relevant and need evaluation.

c. Current laying-in technique.

2. Heating to ignition. This problem depends on the thermal transport properties and on heating technology. We know:

- a. Ion transport at medium to high collisionality may be calculable.
- b. Electron transport is anomalous, but there is some information on scaling in this collisionality range.
- c. Energetic neutral beam heating is effective, and ion heating seems to be understood. Recently, electron heating has also been demonstrated in and explained by ORMAK.

We need more information on:

- a. The spatially resolved dynamics of the heating-ignition process to determine optimum injection scenarios and the power requirements. This information may come from 1-D time dependent transport codes and coupled MHD equilibrium codes and from experiments in present devices. Unfortunately, transport properties at low collisionality are the major unknowns in the area of reactor physics. A completely satisfactory solution of this problem can come only from experiments at low collisionality. Information must be developed concerning when and on which devices this information will be forthcoming.
- b. Very high power beam injection ($P_{inj} \gg P_{OH}$), which has yet to be tried on a tokamak. This experiment is crucial to see whether the plasma can be heated fast enough to conserve flux (especially at the edge regions) and to see whether a limit to the allowable amount of injection power may exist. A limit might arise due to beam-induced instabilities, momentum input from the beams, beam-induced sputtering, and desorption or beam-trapping instabilities. The impurity level in an injection-heated plasma is crucial since with low Z_{eff} (~ 1), 150-keV

energy might suffice in TNS. If $Z_{\text{eff}} > 2$, then beam energies in excess of 200 keV will be required, and a negative ion source development program must be established.

- c. RF heating, especially at the electron cyclotron frequency. This offers promise as a successful heating method and is relatively insensitive to impurity levels. This insensitivity could be a crucial advantage if impurity control proves to be difficult. The basic problem is lack of tube development at the high frequencies required (120 GHz), and hence experimental verification of electron cyclotron resonant heating (ECRH) does not exist at realistic toroidal fields. If ECRH does not succeed in time for TNS, ion cyclotron resonant heating (ICRH) can be used without a major development program. However, the latter is not a first choice because it increases the perpendicular ion energy and can lead to impurity production. Although this problem is predicted to ease as plasma size increases, mode tracking will then become very difficult.
 - d. The effects of flux conservation during heating. To evaluate these effects, we need further development of time dependent codes including these effects. We also need experiments which will produce significant beta. Such experiments are proposed as a second phase in ISX and as a major part of the ORMAK upgrade (OU) program. We need a specific statement about the expectations in these experiments and the methods which will be used to interpret the results.
3. Maintenance of the discharge during the burn phase. After ignition has been achieved, equilibrium and stability must be sufficient to allow some period in which a more or less steady burn takes place. We know very little in this area.
- We need more information on:
- a. Flux conservation time scales. New codes being developed which include flux diffusion will be very helpful.
 - b. How "natural" a current distribution which produces a suitable q profile is; a "nonnatural" distribution would tend to change the equilibrium. Here again, computational results will be helpful. We need to know the relevance of near-future experiments. Will there be sufficient steady state operation to watch current redistribution at high β ? What happens to flux-conserving equilibrium on burn time scales? Can we actively control the current distribution during a burn if something bad happens naturally?
 - c. Instabilities which limit β and which affect the current distribution. Only experiments will tell the extent of such instabilities, but theoretical work is necessary to establish credibility. We need a statement on the likelihood of what information can be obtained from what experiment.

4. Removal of heat. The great amount of alpha heat generated during a successful burn must flow to the outside, assuming that thermal runaway does not occur. This flow will produce large temperature gradients in regions of poor thermal conductivity and may cause stability problems. But these problems may be self-healing. In any event, there is an ultimate loss mechanism which carries the heat from the plasma to the wall. Unless radiation is large, all of this transfer is by particle impact. We know very little in this area.

We need information on:

- a. Thermal and particle transport (1) to establish temperature and density profiles allowing estimation of the significance of synchrotron losses and (2) to permit calculation of impurity radiation losses.
 - b. The physics of the plasma-wall interface. Specifically, we need to know diffusion rates in the shadow of the limiter or divertor plate, surface reemission properties, and the deposition profiles of whatever heating and fueling methods are used. Most or all of this information probably can be provided by present experiments with proper diagnosis.
 - c. The interactions in a divertor box and the extent to which their effects propagate back into the main chamber. Here again, much can probably be inferred from experiments in present devices with proper diagnosis, and many features are amenable to calculation. More direct information may come from PHX.
5. Ash removal. Helium, the ash of the fusion reactions, must certainly be removed in a reactor if it is to operate for a long time. However, in TNS, the fractional burnup will only be a few percent so that TNS can probably operate with no ash removal. Indeed, TNS must be regarded as the primary place to study ash removal since it will certainly be required in EPR or DEMO. TNS will provide information on
- a. helium transport,
 - b. the characteristics of a burn in which helium is allowed to accumulate, and
 - c. the heat removal implications (No. 4 above) yielding surface refluxing rates which bear on the possibility of purging the ash.

6. Particle replacement. Since the fractional burnup will be small in TNS (as discussed in the last section), particle replacement will only be necessary to account for a finite particle-confinement time. TNS will serve as a primary test bed for various fueling schemes.

The density profile will be controlled by particle balance considerations and particle transport properties. It may be that means for replacing deeply penetrating particles are desirable; however, present indications suggest otherwise. Whether or not such replacement is indicated, the technology of fueling is inherently restricted. Deep penetration is difficult, and it is unlikely that any particular region can be fueled without also depositing a significant fraction of the injected particles at greater radii.

TNS will provide information on

- a. particle transport properties and
- b. pellet ablation rates as a function of velocity and plasma properties.

7. Prevention of impurity buildup. Impurity control is essential if TNS is to ignite and burn. Information is needed on:
 - a. Particle transport properties. Under what conditions do impurities migrate preferentially in which direction?
 - b. How fast they migrate.
 - c. How to get this information. We need a statement of the capabilities of the various experiments and their programs.
 - d. Relevance of present data. Can more be extracted from presently existing results concerning, for example, high-Z influx?
 - e. The effectiveness of a poloidal divertor. We need a definitive statement in this area including the possible relevance of PDX results.
 - f. The viability of reliance on a cold plasma blanket in TNS.
 - g. The relative advantages of various limiter configurations if no divertor is used. A belt limiter should be tried in some experiment.
8. The shutdown procedure. The energy stored in the plasma and the magnetic field must be dumped in a manner which does not damage the apparatus and which permits rapid reconditioning for the next shot.

This problem is not expected to be severe in TNS since relatively little energy is stored. Because the plasma may disrupt at any time, unexpected shutdowns must be accommodated.

We need information on

- (a) the behavior of a large discharge when the current is ramped down (PLT and model studies) and
- (b) cleanup procedures (from present experience and ISX).

Table 7 presents a summary of the physics problems ordered according to the above eight points together with an assessment of their priorities.

3.1.3 TNS model

In order to provide a framework for establishing specific physics objectives which must come in a timely manner, we present a model for TNS operation. This model will enable us to narrow the wide range of physics unknowns and to establish priorities.

1. Establishing the current. A large voltage (several hundred volts per turn) is used to break down and initiate a moderate density plasma ($\sim 10^{19} \text{ m}^{-3}$). Currents in the ohmic heating (OH) and vertical field coils are used to prepare a discharge with an acceptable q profile and with low impurity level. For example, $q(0) \geq 1$ is required to insure good stability.

2. Heating to ignition. Massive amounts of neutral beam and/or RF power are used to heat the plasma rapidly enough so that a sequence of flux-conserving equilibria occurs. As the plasma is heated, the flux surfaces shift outward, and the density is increased by means of pellet injection and/or gas puffing.

During this heating phase, the equilibrium evolves rapidly and the poloidal field coil sets will have to be flexibly controlled (perhaps by feedback) to maintain the optimum boundary conditions for flux-conserving tokamak (FCT) equilibria.

As β approaches a few percent, fusion reactions begin to occur at the center of the plasma, and the α -particles can take over heating in the central region. Beam heating which occurs near the outside of the

Table 7. Evolution of physics problems from abstract to specific, focusing on implementation of research needs

Early development				Present development							
Basic physics approach (in the abstract) WASH-1295 1973		Detailed basic physics approach (in the abstract) EPR RD&D 1976		TNS-oriented framework (applied to specific design requirement) TNS RD&D 1977							
Goals (G), Problems (P), Topics (T)		Problem areas	Discharge-cycle oriented	Specific areas in which more knowledge is necessary		Experimental test places and time periods [†]		Priority [*]			
I. Confinement and heating in plasma physics regime (G)	Identified as EPR RD&D #	Title	Evolves into TNS RD&D #	TNS #	EPR # (A-)	TNS #	I	II	III		
A. Configurational stability (P)				1. Establishing the current	8a	1.1	Volt-sec breakdown requirements	v ^a		1	
					6	1.2	Wall-plasma interaction	v ^b		1	
							Clean start-ups/IC during breakdown				
B. Plasma transport and scaling (P)					8a	1.3	Current laying-in techniques	x	x	1	
				2. Heating to ignition	3	2.1	Low collisionality transport properties	v ^c		1	
1. Microscopic plasma transport (T)	A-3	Plasma transport	3		4	2.2	Experimental verification of ECRH at high TF	x	x ^c	2	
2. Scaling laws (T)					4	2.3	P _{INJ} >> P _{OH}	x ^c	v ^{c,d}	1	
C. Heating (P)					4	2.4	Heating profiles, wall loadings in n/c plasmas	x	x ^e	1	
1. Heating (T)	A-4	Plasma heating	2		10	2.5	Impurity CX cross sections	v ^f		1	
D. Boundary effects (P)					1	3.1	Flux conservation time scales (diffusion)	x ^a	x	2	
1. Impurity control (T)	A-5	Impurity control	7	3. Maintenance of discharge during burn phase	2	3.2	Plasma shaping - β as f(shaping)	x	x	2	
2. Plasma material interactions (T)	A-6	Plasma edge	7		2	3.3	Current redistribution for suitable q	x	v ^g	3	
II. Burn for net energy gain (G)	A-7	Fueling	6		2	3.4	Beta limitations	x	x	1	
	A-8	Plasma dynamics	1		8b	3.5	Maintenance of flux conservation	x	x	2	
		a. Start-up	3-6	4. Removal of heat	4, 8b	4.1	Thermal and particle transport	v ^a		1	
		b. Burn control	8		3	4.2	Diffusion rates in shadow of limiter	v ^b		1	
		c. Shutdown			3, 5	4.3	Interaction in divertor box	x	v ^g	1	
III. Other (G)	A-9	Diagnostics		5. Ash removal	3, 8b	5.1	Helium transport	x	v ^h	3	
	A-10	Atomic and molecular cross sections			8b	5.2	Burn characteristic for He accumulation	x	x	v ⁱ	3
					7, 6, 8b	5.3	Heat removal + surface refluxing + ash purging	x	x		3
				6. Particle replacement	7	6.1	Fuel particle transport	v ^b		1	
					6	6.2	Wall recycling, gas puffing	v ^{a,b,j}		1	
					7	6.3	Feasible pellet sizes	v ^{a,b}		2	
					7	6.4	Beam fueling	x ^k		2	
					7	6.5	Ablation rates as f(v, plasma)	v ^{a,b}		2	
				7. Prevention of impurity buildup	3, 7	7.1	Particle transport properties - migration direction and speed	v ^b		1	
					5	7.2	Extraction of present information	v		1	
					5	7.3	Plan for future information	v		1	
					5	7.4	Bundle divertor assessment	v		1	
					5	7.5	Puloidal divertor assessment	x	v ^g	1	
					5	7.6	Cold plasma blanket assessment	x	v ^{a,b,g}	1	
					5	7.7	Limiter configurations	x	v ^b	1	
				8. Shutdown procedure	8c	8.1	Large plasma behavior on shutdown	v ^b		1	
					8c	8.2	Cleanup procedures	v ^{a,b,j}		2	

[†]Time periods:

I = existing base 2/77; present experiments 1976-1978
II = next experiments 1978-1981
III = late experiments 1981-1984
v = will be looked at - more knowledge will be gained
x = will not be looked at in present plan in this time period

^{*}Priority:

1 = critical - go, no-go
2 = important - cost-schedule impact
3 = necessary - needed for final design

Test places/comment

a = PLT
b = ISX
c = PLT/beams
d = ISX/beams
e = except D-III
f = atomic physics
g = PNX
h = general
i = TFTR
j = Alcator
k = bad energy balance

Legend for Table 7

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g = PNX

h = general

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j = Alcator

k = bad energy balance

plasma is now acceptable. During this process, the initial impurity level and its rate of increase must be held small so that beam trapping instabilities do not occur (providing RF heating is not used).

3. Maintenance of the discharge during the burn phase. We assume that the flux-conserving equilibrium will exist during the entire burn phase (~ 15 sec), which is much shorter than the magnetic diffusion time (~ 100 sec). Without a divertor, fueling will be by means of recycling from the wall since only a small fraction of the tritium will be burned. If an unload divertor is used, pellets will be used to maintain density. Because of the short burn time in TNS, ash removal is not critical. However, in reactors it will be essential, and TNS provides an ideal test for this problem.

3.1.4 Physics needs schedule

In the attached chart, Table 8, we have listed the major topics which we identified by means of our TNS model. If TNS, as we envision it, is to operate in 1986, certain facts, trends, and estimates are required at various temporal decision points. For each topic, we have listed the information required at the beginning of each calendar year through 1981.

Once contracts are let in the middle of 1981, designs will have been finalized, and only minor changes and fine tuning can be accommodated by TNS without significant impacts on the TNS schedule. However, we must continue to review the inputs from experiments and theory to be able to decide the priorities of the TNS experimental program and to decide the initial operational modes.

3.2 Primary Design Inputs Poloidal Magnetics and Plasma Shaping

The poloidal magnetics area deals with plasma shape, shaping control, poloidal field coil configurations, and power supplies. The poloidal field system pervades the tokamak device and has direct impact on the machine structure, toroidal field coils, shielding, proposed impurity control systems, remote maintenance, and overall machine and plasma

Table 8. Physics requirements schedule for mid-to-late 1980s TNS operation:
draft of information needs for each part of the discharge-cycle
as a function of time or quality level needed in the TNS project

Topic	Events	Facility conceptual design and cost estimate (4/78)	Start device conceptual design (10/78)	Device conceptual design and cost estimate (4/80)		Let contracts (less 6 months)
		January 1978	January 1979	January 1980		January 1981
Startup scenarios (1) ^a		Preliminary estimate of required breakdown voltage and volt-seconds	Confirm models by comparison to experiment	Know required breakdown voltage and volt-seconds; choose scenario for establishing current profile		Quantify power and energy requirements
Ignition scenarios (2)		Develop scenarios for heating and fueling to high β	Investigate burn control (theory)	Demonstrate heating and fueling to high β		Quantify peak and average power loads
Heating (2)	Beams	Preliminary choice of energy	Demonstrate $P_{AUX} \gg P_{OH}$ at megawatt power levels	Finalize energy and injection angle	Decide on dominant method and estimate power levels	Decide on power requirements
	RF	Preliminary choice of schemes		Choose frequency and antenna structure		
Configuration (shape) (3)		Circular vs noncircular	b/a, δ for "D" aspect of doublet	Determine best plasma shape		Exact dimensions specified
β (3)		Preliminary theoretical estimate of β limits	Increasing confidence in high β from theory and experiment	Experimental demonstration of $\beta > 5\%$		Enough β knowledge to predict wall loading and ignition with confidence
Poloidal field systems (3)		Conceptual design of poloidal field system	Experimental test of high- β equilibrium control	Demonstrate control of equilibrium during the approach to high β		Finalize poloidal field system
Confinement scaling: a, B_r , n (3)		Confirm attainability of high n and n _r in medium-sized tokamaks	Increasing confidence in confinement scaling	Synthesize confinement scaling laws in relevant physics regime		Be able to calculate power levels
Fueling (4, 5, 6)		Test various possible schemes for particle input	Demonstrate pellet injection, gas blankets, puffing, and recycling in medium-sized devices	Pick fueling scheme		Quantify fueling requirements
Removal of heat (4) Ash removal (5) Particle replacement (6)						
Plasma edge (outward particle and energy losses) (4)		Preliminary estimates of fluxes to limiter and walls	Calculate content, spatial and temporal dependences of fluxes	Have a scheme for absorbing fluxes on material walls consistent with fueling, heating, and impurity control		Quantify particle and energy flux absorption scheme
Impurity control (7)		Preliminary decision on impurity control scheme; decide on use of divertor	Experimental demonstration of impurity control in moderate-sized tokamaks	Confirm impurity control scheme		Quantify impurity control requirements
Shutdown (8)		Develop some scenarios	Consider shutdown due to fault conditions	Have a credible scheme		Quantify control scheme

^aNumbers in parentheses refer to discharge-cycle-oriented breakdown presented in Table 1.

accessibility. As a result, early design inputs from this area are of utmost necessity. In an organizational sense, this complex arrangement of individual systems will be treated in an overlay fashion, as will the three other complex areas, field/size, heating, and particle control.

The choice of the poloidal field system is largely dictated by the choice of the plasma cross section, which in turn must be compatible with the physics requirements of the gross plasma stability and confinement. Experimental studies of plasma confinement are being and will be carried out in such devices as PLT, TFTR, and Doublet III. In the area of gross stability, recent theoretical calculations indicated that for critical stability, the volume-averaged $\bar{\beta}$ values in D-shaped plasmas can be 2 to 3 times those of a circular plasma and hence may be comparable to doublet plasmas. Simultaneous calculations also showed that the D-shape is a natural consequence of high β in a flux-conserving tokamak (FCT).

In view of the impact that the plasma cross section has on the reactor design through its poloidal field system, a resolution between D-shaped and doublet plasmas is called for in terms of their high β capabilities and potential engineering limitations. Doublet IIA and Doublet III devices will provide experimental evaluation of the doublet concept. There are as yet no devices dedicated to the verification of the FCT and the D-shape concept. Such devices are indispensable for a proper choice of the TNS plasma cross section. This section summarizes current developments and understanding on the subject of plasma shaping and $\bar{\beta}$ values, and indicates the required experiments that will strongly impact the TNS reactor device.

3.2.1 Review of current developments and understanding in plasma shaping and $\bar{\beta}$ values

3.2.1.1 Theoretical

1. Calculations of high- $\bar{\beta}$ (above 20%), high- q (safety factor, $q_a \approx 5$) equilibria in an FCT indicate that equilibrium requirements do not set limits on the achievable β values. It is also shown that plasma evolves naturally into D-shape as β increases in FCT.

2. Stability requirements may limit β . The Princeton PEST code shows a $\bar{\beta}$ limit of 1.6% in TFTR (corresponding to an RMS $\bar{\beta}^*$ of 1.9%), based upon nearly circular plasmas for ballooning modes. For a D-shaped equilibrium in an FCT, the ORNL MHD simulation code resulted in a $\bar{\beta}$ limit of 4.5%. Similar calculations for doublet plasmas may be in progress. It is now generally accepted in the fusion theory community that with some shaping, $\bar{\beta}$ values of 5 to 10% are likely to be feasible.

3. Effects of shaping to increase plasma β for stability have been estimated by many workers. The current consensus seems to be that (a) the effectiveness of shaping decreases strongly with increasing q_a/q_o (i.e., the degree of peakedness in the profiles) and (b) for realistic profiles, shaping increases β by a factor of about 2 and has a maximum effect at modest degrees of noncircularity.

4. It is believed that vertical field coils external to the TF coils are adequate to position circular plasmas and that closely fitted equilibrium field coils are necessary to maintain doublet plasmas. Recent ORNL equilibrium work has shown that properly placed external equilibrium field coils can maintain D-shaped, high- β plasmas; many questions remain concerning the practical implementation of this analytical result.

5. ORNL estimates of energy balance requirements for a TNS-like, D-shaped ignition tokamak show that with reasonable pressure profiles ($B_T = 4.3$ T and $n_o \approx 1$ to $3 \times 10^{20}/m^3$), two benchmark $\bar{\beta}$ values emerge:

- (a) At $\bar{\beta} \approx 3\%$ ($\beta(0) \approx 10\%$), central D-T ignition occurs with $P_\alpha \approx 50$ MW.
- (b) At $\bar{\beta} \approx 7\%$, "overall" ignition occurs with $P_\alpha \approx 200$ MW.

3.2.1.2 Experimental

1. Recent ORMAK injection heating experiments (Tokamak Experimental Section, ORNL Fusion Energy Division) have successfully produced and maintained plasmas with $\bar{\beta} = 1\%$ and $\beta(0) \approx 3\%$. In these equilibria, $q_a/q_o \approx 4$, $q_o \approx 0.6$, and significant sawtooth activity is observed at $r \leq a/3$ without substantial loss of plasma confinement. It is evident that the β stability limit is nearly reached around the plasma center.

The sawtooth oscillations are present as $\beta \rightarrow 0$, so the connection to the β limit is unclear.

2. We have indirect information indicating that Doublet IIA may have recently obtained discharges with $\bar{\beta}$ close to 1%. We hope that such results will be documented and substantiated soon.

3. Feedback controls have been successful in positioning nearly circular plasmas. Doublet IIA plasmas evolve into droplets or singlets on a time scale of 5 msec if no active feedback control is applied. By active control of currents in several E coils, the doublet shape has been maintained for roughly 20 msec.

3.2.2 Experiments crucial to the TNS program

1. Experimental verification of confined high- $\bar{\beta}$ tokamak plasmas is needed. Demonstrations of $\bar{\beta}$ values around 3% and around 7% in a plasma with q_a/q_o ranging from 3 to 5 are called for. Such values of $\bar{\beta}$, if achieved in TNS, will permit control ignition (near 3%) and overall ignition (near 7%) in D-T plasmas. In view of the PPPL and ORNL stability calculations, a D-shaped plasma (with $\sigma = 1.6$) is called for. The ISX facility fits this requirement.

2. Comparative experimental studies of D-shape and doublet plasmas are needed: A high-temperature, high- β tokamak experiment with D-shaped plasmas and necessarily with an FCT-compatible poloidal field system should be undertaken in parallel with a doublet tokamak. These studies will assess their relative advantages in

- (a) attaining high plasma $\bar{\beta}$ with gross confinement,
- (b) maintaining plasma shape at high temperature and β over long pulses, and
- (c) reducing the engineering problems associated with the different plasma shapes.

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4. TECHNOLOGY RESEARCH AND DEVELOPMENT ASSESSMENT

4.1 Introduction

This section presents a prose summary, program schedule, and R&D assessment discussion for each of the pertinent systems identified in the WBS (see Fig. 4 for an illustration of the systems in the device portion and Part IV for the entire WBS). The names of the individuals principally responsible for assembling information on each system are listed at the beginning of the summaries.

The prose summary for each system includes physics and schedular considerations, in addition to a technology R&D assessment. Specific R&D design problems are summarized and discussed in Part III, and are not included in the prose summary, but are referenced on the program schedules.

The TNS program schedule for each WBS system in the device portion of the project provides in chart form an overall summary for the R&D assessment (physics, technology, and design specific) and construction schedule. The overall construction schedule identifying the integration of individual WBS systems is presented in Part IV.

4.2 Schedule Charts

Each schedule chart contains six principal pieces of information:

1. the particular pieces of physics information needed at each design review to guide specific technology choices in this WBS system;
2. the principal R&D support program schedule;
3. the principal design and construction schedule elements leading to preoperational testing;
4. the design-specific tasks that are associated with the system;
5. a summary event line on which each key requirement or milestone is indicated along with two key distinctions:
 - a. ∇ - action by TNS, review by others,
 Δ - action by others, review by TNS,
 - b. Δ^+ - event presently programmed by DMFE,
 Δ^- - event not currently programmed by DMFE;

6. a judgment of probability of achieving the projected time increment is made for each individual element of the schedule:

- ☐ likely — with business as usual atmosphere,
- ☒ possible — with aggressive atmosphere,
- ☒ conceivable — with totally optimistic program;

7. a summary judgment about this particular WBS area.

These charts and prose summaries provide a concise representation by WBS system of the TNS R&D assessment and the timing interface with the construction schedule. Figure 5, the chart for TF coils (WBS 22c), shows how each of these six pieces of information is entered on the charts; the circled cardinal numbers refer to the six points above.

The technology R&D assessment discussion presents an evaluation for each pertinent WBS system aimed at answering the following questions:

- Is there a basis for support to initiate conceptual design now?
- Is the base focused? and if not
- What is required to focus?

For each of these questions, the following guidelines were established to address specific issues:

- Basis for support
 - extent of knowledge
 - people availability and training
 - facility and funding availability
- Base focused
 - assessment of program needs
 - assessment of program priorities
 - assessment of program coordination
- Requirements possibly needed to focus
 - redirection
 - reorganization
 - increased funding

Fig. 5. An example of the program schedule chart prepared for each WBS system. The circled numbers 1-7 are keyed to the discussion in Sect. 4.2.

4.3 Toroidal Vacuum Vessel (WBS 22a)

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February 1977

4.3.1 Summary

The technology base for the design and fabrication of the vacuum vessel exists. However, material requirements for the first wall liner and the plasma limiter are dependent on physics criteria which are presently undefined. The limiter and liner provide a possible source of plasma contamination, and high-Z materials used in previous devices, including tungsten and molybdenum under evaluation for TFTR, may not be suitable for TNS requirements. Therefore a TNS materials study based on specific physics criteria is necessary. These criteria are (1) the base pressure and operating temperature, (2) the incident particle flux and allowable impurity level, and (3) electromechanical forces due to eddy current loading and plasma disruption loading as a function of time vs energy.

Overall timing for the events and milestones on the following schedule appears to provide no setbacks to the overall schedule. Should a lack of physics criteria go beyond the conceptual design phase, it is not anticipated to have a significant impact on design.

In addition, several other RD&D needs have been identified which will optimize the vacuum vessel design. These are:

1. Radiation damage and mechanical properties at elevated temperatures for candidate materials. Some of these data are expected from fission reactor materials programs, and specific data could be generated from new fusion materials test programs.
2. Development of mechanical seals in lieu of welding for vessel penetration (i.e., diagnostics). This design and development experience is expected from TFTR.
3. Verification of materials performance under plasma conditions. Potentially useful data will be generated from ISX, PDX, PLT, and TFTR.

4. Selection and subsequent demonstration of structural dielectric materials for the vacuum vessel. It is expected that TFTR will provide these data.

Additional comments on the structural aspects of the device will be found in the machine structure discussion.

Figure 6 is the program chart for the toroidal vacuum vessel.

Fig. 6. Program chart for the toroidal vacuum vessel (WBS 22a).

4.4 Machine Structure* (WBS 22b)

E. S. Bettis H. E. McCoy W.C.T. Stoddart P. T. Spampinato

February 1977

4.4.1 Summary

The technology base exists for the design and fabrication of the overall machine structure. However, several areas require further development in order to achieve design optimization. These are:

1. The mechanical properties of materials at cryogenic temperatures. This area is to be addressed by the National Bureau of Standards at Boulder.
2. Radiation effects on materials properties at elevated temperatures. This area is being studied by ORNL-DMFE materials test program and fission reactor programs requiring an input from TNS.
3. Development of analytical methods for induced transient loading on structure and components. Liaison with the TFTR final design is required.
4. Structural design criteria. While not necessarily a development need, these criteria require consideration prior to and during conceptual design. Definition of all loading conditions, margins of safety, environmental safety, etc., will form the basis for design. Lack of established criteria will penalize the design with costly conservatism. We do not envision any primary structural tests, provided the configuration evolves into a structurally determinant arrangement.

Figure 7 is the program chart for the machine structure.

4.4.2 Discussion of Machine Structure (WBS 22b), Remote Servicing (WBS 25a), and Assembly Test Facility Mock-up (WBS 22g) -
W.C.T. Stoddart

The first question to be addressed is, does a basis of support exist to initiate the TNS design, relative to machine structure, remote

* Includes all of the tokamak structure except the toroidal vacuum vessel and conductor structure within the coil cases.

Fig. 7. Program chart for the machine structure (WBS 22b).

maintenance, and assembly test facility? There appear to be no major gaps in knowledge which will prevent starting on the design of the machine structure. There are certainly difficult design problems to be solved to produce a sound structure, but no totally new problem areas exist. Consideration of the environment, loads, and the size of the machine structure for TNS have all been present in engineering efforts for various civilian and military projects in U.S. technology. TNS will simply synthesize these disparate experiences to form a unified solution. There is an adequate base of trained engineers from which to draw, and the facilities required to obtain the necessary materials data and fabrication knowledge exist. The specialized needs of remote maintenance and detail design will be developed and demonstrated in an assembly test facility or mock-up. The capacity of current computer codes is sufficient for the task even though certain loads such as eddy current effects are poorly characterized now. Also, national safety-related standards and criteria do not exist for this type of system, and these should be developed in the process of engineering TNS. It is too early to begin detailed remote maintenance design and development; however, the entire machine structure must be designed to accommodate this requirement.

For a TNS planned to be built in the next decade, there are adequate structural materials. Because of this near-term goal, development and production of any new materials or alloys is unrealistic. Thus, austenitic stainless steels or perhaps some aluminum alloys are the material choices. Considering the complexity of the TNS as currently conceived, the need for several generations of assembly test facilities is obvious. A wooden mock-up is needed to work out procedures and resolve space allocation questions. Additional mock-ups using final design materials and hardware are required to demonstrate previous decisions on remote assembly and maintenance.

The second area of concern is the question of the focus. The current national effort has been focused to a limited degree. The last several years have seen much attention given to the overall concepts of various EPR and power reactor designs. These scoping studies have not

had sufficient commonality to say that a real focus on TNS exists. The centralization of a materials data base effort for cryogenic structural materials in the National Bureau of Standards and of other ERDA programs (i.e., LMFBR for room temperature and elevated-temperature materials) represents a good start. The total national effort in general does not appear to be focused on TNS but could readily be directed if a definition of TNS needs were established; then funding and priorities could be adjusted. This suggests that the highest priority item in the TNS program is to choose a reference design, quantify the appropriate subsystem environments, loads, and performance factors, and communicate these data to the national program.

4.5 Toroidal Field Coils (WBS 22c)

P. N. Haubenreich

February 1977

4.5.1 Summary

Given adequate funding for development, it is considered practically certain a superconducting TF magnet system producing a peak strength of 8 T can be delivered on site consistent with the present TNS schedule. However, critical timing questions exist regarding the integration of the development of a full-size prototype coil, manufacture of TNS coils, and assembly of coils on the device. These questions require further detailed examination, and our current schedule identifies the timing for final assembly to be highly optimistic. The feasibility of a superconducting system with a 12-T peak field is reasonably assured, but development and fabrication if started now are likely to take approximately one year longer than for an 8-T system. Resistive TF coil technology exists, and if this option is used, we do not foresee an R&D program of the magnitude required for superconducting coils. The TF coils are presently a critical path on the construction schedule; therefore, any R&D programs associated with this system will require close attention to minimize schedular impact.

The Superconducting Magnet Development (SCMD) Program, consisting of base R&D, the Large Coil Segment (LCS) Program, and the Large Coil Program (LCP), is working in a coordinated fashion to answer the presently defined development needs of TNS superconducting magnets. This program is investigating the design, fabrication, and testing phases with initial emphasis on 8-T systems because of the ready availability of NbTi. Therefore, development of a 12-T system (Nb₃Sn) lags that of NbTi, but priorities could be reordered if the need for 12 T is definitive. Recent thinking indicates the desirability of a full-size TNS prototype (preproduction) TF coil, and this need will be factored into the next SCMD program plan.

Design input in the form of timely physics judgments about acceptable field on axis, pulsed field, ripple, and plasma size (and thereby

device size) are required to provide correct focus for the TF coil R&D program. This physics input is closely interfaced to our understanding of plasma transport phenomena and scaling laws and therefore will not be forthcoming from a single experiment. Rather, evaluations of all key physics experiments and analytic developments will be an ongoing process and will be factored into the TF coil R&D program; consequently, such evaluations will be a major topic for each of the scheduled design reviews.

Figure 8 is the program chart for toroidal field coils.

4.5.2 Discussion

4.5.2.1 Base for support

Knowledge. The function of the TF system is clear: to provide a low-ripple, steady toroidal field during the plasma pulse. The key performance specification — peak toroidal field strength — is not yet established for TNS. Neither are the magnitude and rate of change of the pulsed fields to which the TF coils will be subjected.

Design options are open over the full range of field strength and pulsed-field environment that are likely to be required for TNS. Each option has important problems, some amenable to design analysis and some requiring substantial R&D to solve. The problems have been identified, and the work required to resolve the problems has been scoped. Schedule and cost can be estimated for each concept and level of performance that may be considered. Given adequate funding for development, it is considered practically certain that some type of superconducting magnet system producing a steady toroidal field with a peak strength of 8 T can be delivered on a schedule consistent with the present schedule for TNS. The feasibility of a system with a peak field up to about 12 T is reasonably assured, but development and fabrication are likely to take approximately a year longer than for an 8-T system.

Function. The function of the toroidal field system is to provide the toroidal component of the field confining the plasma. The primary criteria of performance of this function are (1) field strength at the

Fig. 8. Program chart for toroidal field coils (WBS 22c).

plasma centerline and (2) field ripple at the plasma boundary. For resistive coils operated in a pulsed mode, the criteria are (1) duration of the "flat top" time and (2) pulse repetition rate.

Operating environment. The TF magnet must continue to operate reliably and economically when subjected to

1. centering and deforming in-plane forces due to toroidal field,
2. out-of-plane forces on coils due to vertical field,
3. fatigue effects due to stress cycles during pulsed operation,
4. heating of superconductor by effects of pulsed fields, and
5. heating of coils by nuclear radiation.

The third item, which may be quite important in pulsed, resistive TF coils, can be a problem in superconducting coils if conductor motion due to pulsed fields is not prevented by proper design and fabrication. The last item is not serious for water-cooled resistive coils.

Performance requirements. The criterion on maximum permissible field ripple at the plasma boundary in the final design of TNS will probably be a few tenths of a percent. This criterion is simple to meet, at least in principle: more or larger bore coils can reduce ripple to any desired value (with concomitant increase in cost, of course).

The field strength that will be required in TNS must be determined through a complex plant-optimization procedure (the trade studies are now under way). Clearly the higher the field, the better the confinement or, alternatively, for a given measure of confinement, the smaller and perhaps simpler the plasma systems can be. Attainment of higher fields involves more or greater magnet problems: mechanical design of coil structures, practical limits on energy input to a pulsed, resistive TF system, limits on superconducting regime for different superconducting materials, etc. It now appears most likely that the peak field strength specified for TNS will be either 8 or 12 T. (These values are near the practical upper bounds for different concepts of TF coils.)

The pulsed-field environment that will be encountered in TNS will depend strongly upon the design of the poloidal field system and the dynamics of plasma start-up and shutdown (both normal and abnormal

rates). If the poloidal windings are all located outside the TF coils, the vertical field at the TF windings will range up to 0.5 T. Location inside may bring the magnitude of the pulsed field down to 0.05 to 0.15 T. (The doublet machine would have a more extensive system of poloidal windings near the plasma and would have the lowest pulsed fields at the TF coils.) The rates of field pulsing are important as well as the magnitude. Time for change of field will normally depend upon how the large TNS plasma must be started up; about 1 second for raising the plasma current (and poloidal fields) is presently estimated by various sources, but considerable uncertainty exists. A disruptive instability in the plasma could cause the plasma current to go to zero in 10 to 100 μ sec. Detailed analysis, including shielding or compensating effects of the vessel and poloidal field coils, is needed to assess the probable effects on the TF coils.

Options available. Four major options have been or are being considered by the TNS teams (ORNL-Westinghouse and General Atomic — Argonne National Laboratory).

1. Superconducting NbTi, up to an 8- to 10-T peak field. (Peak fields above 8 T require subatmospheric-pressure helium coolant systems to produce temperatures below 4.2 K.)
2. Superconducting Nb₃Sn, up to about 12-T peak field. (The field is limited to this value by structural and cost considerations.)
3. Resistive, copper, water-cooled, up to 10- to 12-T peak field. (The field is limited by structural considerations. Energy requirements may also limit practical application in TNS.)
4. Hybrid, resistive copper in highest-field portion, superconducting NbTi in lower-field segment.

Identification of major problems. *Structural design.* Any TF coil of TNS size must sustain very large asymmetric forces which must be distributed internally and transmitted to an external structure without excessive stresses and in a manner economical of space and money. For a copper TNS coil, the structural problems would be similar to those being addressed in the 2.8-m-bore TFTR coils, but would be magnified by the larger size. In a superconducting coil there are problems similar to

those in a copper coil, plus the special problem of preventing relative internal motion under pulsed loading in a winding whose conductor must have the largest practicable surface area exposed to coolant (see below). Because superconductor performance is degraded by excessive strain, the structural design must limit strain at all points to less than some tolerable value. Tolerable strain for the ultimate conductor is not accurately defined but is likely to be approximately 0.2% for NbTi and 0.1% for Nb₃Sn (see below).

Heating by nuclear radiation. This is a problem in superconducting coils, not from the standpoint of peak heat flux but because the total enthalpy rise of the coolant over the duration of a TNS ignition pulse may result in excessive vapor (for boiling helium coolant) or excessive coolant temperature (for supercritical helium coolant). The thermal design of the coil may be especially impacted in the vicinity of large ducts penetrating the neutron shield around the plasma. The magnitude of the radiation heating can be limited; the optimum must be determined by an integrated trade-off study in which shield thickness and coil cooling costs and feasibility are considered.

Heating by pulsed fields. The uncertainties in field magnitude and rates that must be endured are discussed above. For rapid transients, various mechanisms produce heat both in the superconductor and in the normal conducting material in the winding. By careful design of conductor and winding it should be possible to insure that pulsed heat generation does not exceed heat removal capability and thereby create a normal zone.

Stability. Production of a normal zone in a superconducting coil during abnormal operating occurrences is tolerable, provided the coil is designed for cryostability, and the decision was made in December 1975 that the U.S. tokamak magnet development program should concentrate on cryostable coils. Cryostability is simple in principle but difficult to apply in coils that must meet all other tokamak magnet requirements. Much design analysis and experimental measurement of thermal performance will be required.

Cooldown. The unusually massive and complex superconducting coils and structure must be brought from room temperature (~300 K) to operating

temperature (3 to 6 K) and back in a controlled manner to avoid excessive stresses. This is a significant coil design problem and also imposes limiting demands on the refrigeration and helium storage system.

Conductor development. The current carried by a conductor in a superconducting TNS coil will be a compromise between considerations of fabrication ease, stability, and coil protection (voltage during quench). At present the expected current is 10 to 15 kA, which is more than that of conductors now in production but within the state of the art. The conductor must be procured and evaluated experimentally to obtain data on pulsed heating, mechanical motion, and heat transfer (stability).

Development work required. A program has been laid out to answer the development needs of TNS superconducting magnets, as presently defined. This program, which includes base R&D and LCP is discussed below.

Industrial support base. Vigorous, effective industrial involvement in development of superconducting magnets for TNS is being assured through the Large Coil Program. Detailed proposals for design and fabrication of 2.5-by-3.5-m, 8-T coils for testing in the LCP were submitted on 15 February 1977 by five major U.S. firms:

General Electric Co. (supported by Intermagnetics General Corp. and Chicago Bridge & Iron Nuclear Co.)

General Dynamics, Convair Division

Grumman Aerospace Corp.

Magnetic Corp. of America (supported by Combustion Engineering)

Westinghouse Electric Co.

The five proposals (totalling 42 cm in thickness) reflect thorough analyses of key technical problems and requirements for fabrication facilities and personnel. All firms appear to be competent to design and produce test coils, but there are substantial differences in technical concepts and manufacturing techniques. All proposed to use some form of NbTi conductor, but some proposed cooling with boiling helium while others concluded that forced-flow cooling will probably prove most practical. The proposals were accompanied by strong expressions from corporation management of their firms' commitment to participate in fusion magnet development.

4.5.2.2 Base focus

Assessment of program needs. The EPR studies and the initial TNS studies have provided the designed criteria and requirements for the superconducting toroidal field magnet. These design projects have given us a firm understanding of the operational features that magnets developed for TNS will have to meet.

Programs ordered. Design work has been conducted on both 8-T and 12-T toroidal field designs. However, the initial experimental work of the program has concentrated heavily on 8-T magnets because of the availability of the conductor. At the present time, the development of Nb₃Sn lags that of NbTi, but the priorities could be inverted if the need for 12 T were definitive.

Programs coordinated. The SCMD Program, consisting of the base R&D Program, the LCS Program, and LCP, is working in a coordinated fashion to achieve the R&D of large magnets for the TNS project. For this effort, both 8-T maximum field magnets employing NbTi and 12-T maximum field magnets employing Nb₃Sn are being investigated in the design, fabrication, and testing phases.

4.5.2.3 Additional requirements

The program laid out in the construction schedule to meet TNS needs is not fully covered by the draft 189s that are now being prepared (February 1977). The schedule shown for LCP is a "normal" rate, which means that one step follows the previous one without any delay or stretchout to hold program costs to a prescribed limit in any fiscal year. The prototype coil is not covered at all in the 189 submission. The rationale and justification for a prototype follows.

Prototype coil. Among the various coils that are built and tested in LCP, at least one will be like the ultimate TNS coil in most important regards (conductor, cooling, structure) and will be tested under TNS-like conditions (current density, peak field, pulsed fields, force distributions, etc.). The justification for any other large coil before the TNS production coils must be examined in light of the substantial

accomplishments in LCP and the ways in which the LCP coils differ from those in TNS.

The LCP coils differ from the TNS coils mainly in that they are half as long (although about the same in cross-section). This difference prevents them from being a true prototype.

In defining the prototype for TNS coils, the following key questions must be addressed.

- What are the essential functions of a prototype?
- What constitutes an adequate prototype?
- When in the overall TNS schedule is the proper time for a prototype (or prototypes)?
- Where (in what kind of facility) should the prototype be built?

Functions. The essence of the prototype role is to provide the final proof of the practicality of the design and the fabrication process that have been chosen for TNS coils.

Characteristics. A true prototype must be the same as the production components in (1) physical size, (2) configuration, (3) materials, and (4) manufacturing methods.

Timing. From the definition of function, it follows that (1) the fabrication must await the detailed design of the TNS coils and (2) the completion and testing of the prototype must precede the beginning of production of the full complement of TNS coils.

Procurement of materials and some fabrication steps need not wait until every detail of engineering is finished. However, the specifications and drawings prepared for use in production should be used for the prototype. If the construction and testing of the prototype reveal inadequacies or possibilities for improvements, evaluations should be made in terms of benefits to TNS and possible impacts on schedule, and decisions should be made whether or not to revise the detailed design accordingly.

Fabrication. The intended function of debugging and proving the fabrication tooling and procedures dictates that the prototype be fabricated by the organization and in the facility that will be subsequently employed for production coils.

4.6 Poloidal Field Coils (WBS 22d) (including the OH and EF coils)

J. K. Ballou

February 1977

4.6.1 Summary

Magnet technology for the design, fabrication and operation of resistive PF coils exists, but these coils could be subject to difficult design problems if some of these coils are located inside the TF coils. (Superconducting coils inside the TF coils would present an even more formidable, if not impractical, problem.) Development of acceptable remote maintenance capability (connectors for coil segments) is presently judged to be a most difficult design problem (Part III, Sect. 1.3-1). These inner coils will be subject to intense radiation fluxes, and the evaluation and identification of acceptable insulation materials to minimize deleterious effects will provide important input for shield optimization, which will affect device size and cost (Part III, Sect. 1.3-2). PF coils located outside TF coils could use superconducting technology. The superconducting technology base exists to initiate conceptual design, if this option is used, and R&D programs have been identified to provide required input consistent with TNS scheduled needs. A critical R&D task for superconducting coils which was proposed in the SCMD work program for FY 1978 is the development of an information base for nonconducting structural materials and potential development of such a material, if necessary. This type of material will eliminate excessive joule heating resulting from eddy currents.

Timely judgments of physics understanding will be required throughout the design phase to provide design criteria for the PF coils. The question of locating the PF coils inside or outside the TF coils requires continuing evaluation. For external coils, the feasibility of maintaining a D-shaped plasma in a high- β FCT must be demonstrated, and the increased cost of power supplies for external coils must be evaluated relative to the difficult design problems associated with internal coils. Physics understanding will be required to provide design criteria

for total plasma power, power distributions, MHD equilibria and stability, and plasma control and maintenance. Impurity control R&D programs could identify additional requirements for the PF coils if a divertor is found to be necessary (Part III, Sect. 1.4-1). This physics input is closely interfaced to our understanding of plasma transport phenomena, scaling laws, MHD equilibria and stability, plasma start-up and maintenance (during a burn) and impurity control, and will not be forthcoming from a single experiment. Rather, evaluations of all key physics experiments and analytic developments will be an ongoing process and will be factored into the PF coil R&D program; thus, such evaluations will be a topic for each of the scheduled R&D programs.

Integration of WBS 22d with the closely related impurity control system 22f and energy conversion system 23c is an essential part of the design and assessment process along with the evolution of physics criteria. Fundamental experience with plasmas using actively controlled PF coils will come from near-term ISX and PLT experiments and must serve as a base for design. The inside-outside coil decision must be made before definite plans for PF coil R&D needs can be clarified.

Figure 9 is the program chart for poloidal field coils.

4.6.2 Discussion

The poloidal field magnet system can be separated into two groups: those that are located between the shield and the TF coils and loop through the bores of the TF coils, and those that are outside the TF coils. The first group is referred to as the EF coils, and the second as the OH coils. The EF coils receive a great deal of nuclear heating and should certainly be resistive, but the OH coils do not receive as much radiation and can conceivably be resistive or superconducting. The following sections will consider all of these options.

There is a considerable base of knowledge to draw from for the resistive coils. The most applicable is the efforts on PLT, TFTR, ORMAK, etc. There is also a good industrial base. The base of knowledge for the superconducting coils is not as large, but work has been done on TNS-related problems at ORNL, GA, ANL, and Los Alamos Scientific

Fig. 9. Program chart for poloidal field coils (WBS 22d).

Laboratory (LASL). To the extent that all pulsed superconductor work is related to TNS, each of the high energy physics labs is another source of knowledge because of their superconducting beam-line magnet work.

There is good focus on the superconducting problems of the OH system, but there is less focus on the resistive EF coils. The OH system has been assumed to be superconducting because of possible power and capital cost savings and because of their applicability to future reactors.

The program needs to address the following areas for the superconducting concept: (1) superconducting pulse losses, (2) superconductor fabrication, (3) nonconducting structural materials, (4) cooling methods applicable to high turn-to-turn voltage applications, and (5) fabrication design scalable to larger size. These areas are being addressed by the SCMD pulsed coil (poloidal) program and potentially by the LASL effort. The only exception is the nonconducting structural materials problem. There will be 189s submitted shortly for the study of these materials. The high turn-to-turn voltage problems associated with the OH system could be helped by a different start-up method.

The EF coils have three interconnected problem areas: (1) remote maintenance, (2) insulation, and (3) joints between segments of the coils. At present, there is no program concerned with the remote maintenance of these magnets. There will be a number of 189s submitted for funds to work on the problems of the insulation materials (material properties under radiation). The joint problem is the most far-reaching in that there appears to be little chance to make a multiturn EF coil system. The design of single-turn EF coils will complicate their power supply problem.

The program needs to be redirected for the EF coil system but appears to be well-focused for the superconducting OH system. The EF coil problems are in the area of design and demonstration except for the problem of the insulator. The insulator work should start as soon as possible so that the design and demonstration can proceed with the correct insulator. The superconducting program seems to be on track, but the time schedule is tight.

4.7 Shielding (WBS 22e)

R. T. Santoro

February 1977

4.7.1 Summary

The existing, funded R&D programs for the TNS provide an adequate base to initiate conceptual design. Uncertainty in the shield system design criteria will principally affect device cost (size), not schedule. However, if active impurity control requires a divertor, development of acceptable shielding for the divertor penetration could affect the present schedule. TNS final design will require some modifications and changes in emphasis; however, the basic R&D programs are in place. A well-defined nuclear data base, substantiated with CTR-focused cross-section data experiments, suitable computational tools (including codes and input data) and an experimental program to validate calculated results, is essentially under way to provide a basis for optimizing shield design.

The CTR data base currently being assembled is generally focused on the needs of the fusion community and should be assessed with regard to specific TNS requirements. Radiation transport computer codes exist and will require some modifications for application to toroidal geometry and for solution of radiation streaming. No suitable code exists for the calculation of accurate distributions of the radioactivity and afterheat. An evaluated activation data library and codes to access efficiently these data will also require development. These calculations are presently performed in many disjointed steps, and increased efficiency and shield optimization will result from an automated procedure. Integral experiments to study the materials and configuration of the TNS shield are funded and under way at ORNL. Future experiments to measure neutron streaming through penetrations in the shield are planned, and these studies will be consistent with the TNS design.

Timely judgments of both physics and technology understanding will be required throughout the schedule design phase to provide design criteria for the shield system. Physics understanding will be required

to provide design criteria for total plasma power, power distributions, and shield eddy currents. Impurity control R&D programs could identify additional requirements for the shield system if a divertor (with attendant penetrations) is found to be necessary. This physics input is closely interfaced to our understanding of plasma transport phenomena and scaling laws, and will not be forthcoming from a single experiment. Rather, evaluations of all key physics experiments and analytic developments will be an ongoing process and will be factored into the shield R&D program; such evaluations will be a topic for each of the scheduled design reviews.

Technology understanding from other R&D programs will be required to provide design criteria for TF coil heat input, heat removal capability, and vacuum vessel penetrations. The LCS and LCP R&D programs are scheduled to provide relevant data on TF coil heat transfer characteristics. Consideration of the impact of penetrations on shield effectiveness will be closely interfaced with neutral beam and diagnostics programs.

Figure 10 is the program chart for shielding.

4.7.2 Discussion

4.7.2.1 Nuclear data

The CTR data base being assembled at the Radiation Shielding Information Center; the CTR cross-section data experiments funded by the Division of Physical Research and being carried out at ORNL, Duke University, and elsewhere; and the pulsed sphere experiments at Lawrence Livermore Laboratory are major funded programs that are supplying nuclear data to the CTR community. The extent to which these programs address the goals and commitments of the TNS program should be assessed, particularly to assure that the experiments are securing cross-section data for elements of interest to TNS.

Nuclear data needs. Code development for processing cross sections, radiation damage data, and kerma factors are generally adequate. The modifications to the MACK code for producing neutron kerma factors from

Fig. 10. Program chart for shielding (WBS 22e).

ENDF/B-IV data should be completed and tested for the materials of interest to TNS. The CTR multigroup library should be evaluated in TNS conceptual designs.

Nuclear data measurements should be concentrated on materials of interest to TNS. These include the isotopes of some elements in stainless steel (Fe, Ni, Cr), Ti, and W (the latter two being of interest in impurity control systems). The nuclear data evaluations should be maintained and improved as the results of these measurements become available.

The incorporation of evaluated activation cross-section data in the ENDF/B-IV files is essential for accurate determination of induced radioactivation and afterheat. Codes to process these data must be developed.

4.7.2.2 Radiation transport methods and codes

One-dimensional discrete ordinates. The existing codes (ANISN, DTF-IV, ONETRAN) are suitable for the solution of the one-dimensional class of problems of interest in the TNS design.

Two-dimensional discrete ordinates. The existing codes (DOT, TWOTRAN) are amenable to the solution of a large number of problems. The incorporation and development of a triangular mesh should be completed. Investigations to determine ray effects and other two-dimensional computational anomalies in CTR application should be investigated. No other major code developments are envisioned.

Three-dimensional discrete ordinates. No development is warranted.

Monte Carlo. Monte Carlo codes exist that are generally adequate for solution of three-dimensional radiation transport problems, particularly radiation streaming through shield penetrations. The inclusion of approximate and/or detailed representations of toroidal geometry should be reviewed. Biasing and sampling methods for radiation-streaming calculations must be investigated to assure accurate estimates of the effects of penetrations on vital TNS components.

Radioactivity and afterheat. No suitable code exists for the calculation of accurate distributions of the radioactivity and afterheat.

The remote maintenance problems, safety analyses, and the effects of radiation on the environment must be determined for TNS with more confidence than with the codes and uncertain data currently being used. The code to be developed should access an evaluated data library (which also requires development) and produce, for the appropriate geometry, distributions of the radioactivity, afterheat, and other basic radioactivity data.

4.7.2.3 Integral experiments

Integral experiments to study the materials and configuration of the TNS shield are funded and under way at ORNL. The experimental program is in its earliest stages and is being tailored to identify and test the effectiveness of the bulk shield materials proposed for use in the TNS. The results from these experiments are important for establishing basic reactor dimensions. Future experiments to measure neutron streaming through penetrations in the shield are planned, and these studies will be consistent with the TNS design.

4.8 Impurity (and Gas Throughput) Control Systems (WBS 22f)

A. T. Mense

February 1977

4.8.1 Summary

Impurity control in tokamaks is essential. Impurity control systems, if they are required, can have a significant impact on the overall design of the tokamak device. Unfortunately, at this time, the requirements of such systems are not fully understood, nor has their necessity been firmly established. Because this major component of the machine represents a go or no-go situation for ignition, the need for impurity control information is well recognized in the fusion community. As a consequence, all major fusion devices will be developing plans, sometimes little more than recipes, to produce low- Z_{eff} plasmas. It is not clear that any systematic efforts for impurity control studies are planned, with the exception of the ISX work. If large experiments can reach an operating regime which allows ALCATOR-type operation (low edge temperatures and low Z_{eff}), then no active impurity control technology need be developed. There are generic technology studies involving limiter materials and vacuum systems which should be actively pursued, possibly in conjunction with other function agencies (NASA, etc.). Some scheduling of impurity studies experiments over the experimental lifetimes of current planned experiments is needed to prevent undue overlap and to allow optimal cost-benefit ratios.

The program chart for impurity control systems is not yet available.

4.8.2 Discussion4.8.2.1 The elements of impurity control

Impurity control in tokamaks is essential. Even with a great deal of experimental data, the theoretical understanding of the impurity problem is meager, and no present theory can be used for the prediction of TNS operational scenarios.

A systematic experimental development and enhanced theoretical program is necessary. Fortunately the entire worldwide plasma community seems to recognize the importance of impurity control; and all present and planned devices, to the best of our knowledge, include as many measures as deemed feasible to improve the cleanliness of the discharge.

There has been in the past a premium placed on achievement of high temperatures. In ohmically heated discharges, this heating is enhanced by the pressure of low-Z impurities. With the development of high power neutral beams and RF heating, one may now proceed to higher temperatures with cleaner ("fusion grade") plasmas.

The important points in the impurity control question are:

1. Can we control the high- and low-Z impurity content during the breakdown phase of the discharge?
2. Can we extract from the experimental data sufficient information to determine impurity diffusion rates? Does VT play an important role in impurity diffusion?
3. Will some type of "wall treatment" enable the discharge to remain relatively clean throughout the burn?
4. Can divertors really handle the particle fluxes and heat loads predicted for future devices?

There are devices capable of answering most of the above questions. It is not clear, however, that there is enough experimental resource available to pursue all these questions within a time frame compatible with a 1986/88 TNS construction date.

4.8.2.2 R&D needs for support of impurity control methods used on TNS

1. Study is required of on-the-wall gas saturation and hold-up mechanisms and of the use of wall coatings to prevent initial impurity contamination.
2. Study is required to establish discharge "dynamics" (e.g., small radius-expanding magnetic limiter) during breakdown through the full-power phase of the cycle. One must assess whether or not particle collection by the divertor is necessary and/or possible during breakdown.

3. Mechanisms for expanding plasma size and "laying in" a reasonable current density profile during expansion must be considered.
4. Intermediate-Z impurities in plasma can be tolerated if they can be made to remain near the "edge" and if they are not prevalent near the edge during the beam heating phase. RF heating should be actively pursued as an alternative to bulk plasma heating if edge impurity concentrations can not be reduced to manageable levels for the start-up phase.
5. Studies should be conducted on methods to handle large transient heat loads in the particle collection chamber of a divertor.
6. Studies must be conducted on establishing a cold plasma (maybe even a low- Z_{eff}) blanket at the plasma edge. This blanket may be established through the use of a divertor or possibly without a divertor. One would like to maintain a reasonably low edge density during start-up to allow maximum beam penetration and minimum edge heating.
7. Studies should be conducted for materials which will selectively trap the wall material impurities but not deuterium and tritium.
8. Can one find a high-temperature helium pump for transient He loading?

4.8.2.3 Proposed experiments to answer the above questions, nos. 1-8

1. Most devices could address impurity contamination, but ISX, ISX-II, and PDX are probably the best equipped in terms of physical layout. PLT, however, needs to address this seriously in order to go to lower Z_{eff} .
2. PDX will study discharge dynamics extensively, but we need to have experiments address particularly methods of either handling or decoupling the heat loads from the particle flux to the divertor chamber.
3. Plasma size and density profile need to be addressed by all experiments, but probably PDX and ISX are best.

4. PLT, ISX, and PDX will be of interest. Use of ECRH in ISX might be of some interest. The time scale to get high power ECRH may be too long. RF heating should be pursued on PLT.
5. Transient heat loads must be addressed on PDX and ISX-II. Some work could be done on interactions between the wall and gun plasma.
6. Work on the cold plasma blanket can be done in principle on PDX, ISX, ISX-II, and Doublet (without divertor).
- 7 & 8. No work is currently under way in these areas.

4.9 Mock-up Systems (WBS 22g)

P. T. Spampinato

February 1977

4.9.1 Summary

The TNS mock-up will serve to identify design problems, demonstrate design integrity and verify all aspects of the remote handling systems. The mock-up systems require a design baseline in order to accurately represent the device configuration. With this baseline technology established, mock-up development can begin during the conceptual design phase of TNS, and the first stage model can be completed after the conceptual design.

The following outline defines our present understanding of mock-up development.

- Stage I: full-size wooden model of one coil and a vacuum vessel segment, to be completed six months after conceptual design. This model will demonstrate design integrity.
- Stage IIa: full-size metal model of 2 coils and a vacuum vessel segment (including shielding and support structure) with appropriate hardware. This mock-up will be completed in 1981 and will demonstrate remote operations such as cutting, welding, leak detection, and viewing.
- Stage IIb: by adding the neutral beam mock-up and diagnostics to the IIa model, a complete segment of the device will demonstrate and optimize all remaining handling systems as well as assembly and disassembly. This model should be completed before the final design review.

Additional comments can be found in the machine structure discussion.

Figure 11 is the program chart for mock-up systems.

Fig. 11. Program chart for mock-up systems (WBS 22g).

4.10 Electrical Power Systems (WBS 23)

J. K. Ballou W. R. Becraft
C. M. Loring N. S. Ponte

February 1977

4.10.1 Summary

The technology base in electrical systems exists to support the initiation of a conceptual design for TNS. There are two areas that require increased development effort. One is the neutral beam electronic switching system, which will need accelerated development if the required particle energy exceeds 150 keV; the other is the poloidal field electrical equipment, which accounts for a disproportionately high share of the TNS cost projection.

The critical gap in the electronic switching (the absence of the required tube capabilities) is detailed in the following discussion. The switch will not only be required to operate at voltages above 150 kV, but also for pulses of over 10 sec. These requirements can only be met with a major vacuum tube development program that must get under way in FY 1978.

Energy conversion (WBS 23c) for TNS can be achieved with available technology, but at costs that are projected to be exceedingly high. Motor-generator-flywheel sets, along with solid-state devices and mechanical switches, can supply the expected poloidal field electromagnetic energy requirements but at costs exceeding \$100 million. In addition to the cost, there are serious concerns that must be addressed relating to the need to gang large numbers of elements. Preliminary studies indicate that acyclic-homopolar machines may allow reductions in the PF system cost as well as offering a lower rotating machinery cost. These analyses must be pursued, and if the results warrant, an accelerated homopolar generator development program should be undertaken.

The remaining electrical power systems areas can be developed with no major system or component advancements required. The primary energy (WBS 23a) R&D effort must include the modification and use of electrical system harmonics. In addition, the electrical grid's ability to provide energy storage and the resulting TNS system simplification and cost

reduction will be determined in a TVA-ORNL cooperative study. Primary and secondary distribution (WBS 23b) is expected to be accomplished by using available commercial equipment. Standby and emergency power (WBS 23d) requirements to maintain the integrity of TNS are judged to be achievable with techniques and procedures that have been and will be developed for other highly technical and complex devices.

Figures 12 and 13 are the program charts for primary power and energy conversion.

4.10.2 Discussion of neutral beam injectors — N. S. Ponte

Electrical-electronic factors for plasma heating by neutral beam injectors. Neutral beam injectors for PLT and ORMAK Upgrade are designed to operate at 40 kV, 60 A. An electronic switch utilizing a tetrode vacuum tube must be used between the high voltage dc power supply and the accelerating electrode (target cathode) of the ion source. This switch must be capable of opening the circuit under fault conditions in tens of microseconds followed by reclosure after a few hundred microseconds delay. Without this vacuum tube switch, destructive energy from the power supply will damage the ion source grids.

At the 40 kV level, electronic equipment can utilize large vacuum tubes which were designed for commercial and military applications. These types are indicated on the accompanying chart. For power supply regulation and transient considerations, the reliable output voltage operation is about 75% of the rated tube hold-off voltage. Up to 40 kV, new tube developments have not been required to support plasma heating research.

For the next generation of ion sources, tubes capable of 100 kV hold-off and 80 kV delivered to a source are limited to only three types from two manufacturers as indicated in Fig. 14. These are modified commercial types. Since none are yet in operation on test stands, their performance and reliability are undetermined.

To support TFTR, two tube developments were funded by Princeton Physics Lab starting in FY 1976 with completion scheduled by end of FY 1977. RCA and Eimac Division of Varian are the two subcontractors.

Fig. 12. Program chart for primary power (WBS 23a).

Fig. 13. Program chart for energy conversion (WBS 23e).

Fig. 14. Switch tubes for neutral beam injectors.

Development goal is a 200-kV switch tube to deliver up to 150 kV for 1-sec pulse to an ion source. Both contracts are cost plus fixed fee (CPFF); thus final cost and performance can be measured at the conclusion or cessation of development. Semiconclusive test data may be available by the end of FY 1977. It is imperative that several of these prototype tubes be incorporated as they become available into ion source test stands, where their reliability can be determined under actual operating conditions. For a TNS application with pulse lengths >10 sec, further development may be necessary as indicated by long-pulse test data.

Neutral beams operating above 150 kV will require a major vacuum tube development program. It must be started by the end of FY 1977 to meet the Title I schedule, FY 1980. There are three or more U.S. manufacturers capable of undertaking this development challenge. Again, prototype tubes must be run on test stands for one year of operation to meet Title II by FY 1981.

To support a mid 1980s goal of a working power reactor, the following specific action is necessary:

1. A joint decision by the national laboratories on the likely range of neutral beam injector voltages and currents must be made by the end of FY 1977.
2. By that same date, a survey of vacuum tube manufacturers' capabilities should be completed and development contracts let to at least two companies for competitive reasons.
3. These development contracts are likely to be CPFF. Consequently, progress of the development should be continuously monitored and evaluated by a resident engineer at each company. Detailed weekly reports should be provided to the administering laboratory by this resident engineer.
4. Failure to develop a tube capable of reliable performance at required voltage and current will directly affect the schedule for Title I and beyond.
5. Tube development is a major, mandatory component requirement. No development work is being done at this time other than that on 200 kV, one-sec pulse length.

6. Investigative funding is required in FY 1977 with development contract funding by FY 1978.
7. No alternative technology for high voltage switching at the required fast rate is known at this time.

4.10.3 Discussion of poloidal field electrical system — J. K. Ballou

1. Knowledge base. There is considerable knowledge in the area of power supplies suitable for operating the poloidal field system for TNS. This base of knowledge is in the several industrial corporations that manufacture electrical generating equipment in the United States and the rest of the world, in the various electrical power utilities, and in the national laboratories that have studied and built tokamak devices. In addition, there have been a number of feasibility studies concerned with energy storage carried out by universities and national laboratories in the past several years.

There are plans to make facilities for large-scale experimental work available at LASL. Detailed plans for this facility have not been published to date, nor has there been an estimate for the cost of the facilities.

2. Base focus. This is a very large base, and it may not be necessary to focus all of it on this problem. The base at the national laboratories concerned with tokamak fusion is focused on TNS.

One of the major needs of the program is an innovative start-up method that does not require a plasma loop voltage of several hundred volts for some time during start-up. The present system requires a high overall voltage on the OH magnets. This requirement makes the electrical breakdown of helium (in the case of superconducting OH magnets) a major problem and consequently brings the reliability of the system into question. In addition, the high voltage affects the power rating of the components and boosts the system cost. This innovative approach could help upgrade the system's reliability and reduce its cost. The present system appears to be feasible with present methods but at high cost.

Until an innovative start-up approach is developed, the program is correctly ordered to investigate both conventional approaches having the

highest priority. TNS should not be handicapped too much with overly efficient energy usages. Tens of percent of the potential electrical output could be wasted for this machine (for start-up), and still TNS would be a success.

The most attractive way to operate a superconducting pulsed magnet is to energize it slowly, then remove its energy rapidly to get the necessary pulse. The reason for this is the behavior of the superconductor's critical temperature with magnetic field. As the field is reduced (by reducing the current), the critical temperature increases. So even though heat is being added to the magnet by various mechanisms, the critical temperature is increasing, giving an added margin of safety. It is possible to operate a tokamak in this mode, but the EPR design did not use this mode because of the very high field required (about 14 T). But TNS will only require 4- to 6-T maximum field for the one-way flux swing. Because of the added safety margin and because the plasma will operate well within this mode, this method should be pushed for the OH power system first.

The power supply for the EF coil system is not as clear because of the control aspects of the EF coil system. These magnets help control the plasma shape and position and must, therefore, be able to respond with the appropriate speed. The speed is determined by the interaction of the plasma and the shield. This interaction must be carefully evaluated and integrated into the EF magnet power supply system, which in turn requires a close interconnection with the instrumentation and control systems. At present, there is not sufficient interaction of these two areas because work on the instrumentation problems is just now getting under way. Funding necessary for the poloidal field electrical system will be difficult to determine until more work has been done on the plasma-shield interaction and the instrumentation system.

3. Requirements. Some increase in the funding for power supply systems is in order for the next year or two, but when it is known what type of start-up method will be available, the funding should be evaluated again. Five man-years is required in FY 1978 to scope the options and begin plans for a facility to test the power supply system.

4.10.4 Discussion of OH circuit switching — C. M. Loring

Two alternatives exist to meet the high-current, high-voltage switching requirements (10s of kA at 25 kV and up): mechanical vacuum dielectric switches and assemblies of many solid state (thyristor) devices. The following data is required: more specific voltage, current, allowable interrupting time, frequency of interruption, duration of current carried by closed contacts.

1. Present devices. The largest vacuum switch is a relatively untested device made by General Electric. It is proprietary, and little information on it is available at this time. Its parameters promise capability in excess of 50 kA at voltages in excess of 40 kV. Its design permits cooling of the arc shield — essential for frequent interruption. Other switches with capabilities in the 30 kA region at voltages of 20 to 40 kV are made by several manufacturers. All vacuum switches suffer from limited life due to contact erosion during interruption arcing. Switch (vacuum "bottle") development can improve life somewhat, but life improvement just as or more promising can be achieved by improving actuating mechanisms and commutating circuits in order to minimize coulomb transfer in the arcing interval.

Thyristors developed for dc transmission line service can handle currents of a few kA at voltages to about 2 kV per device. Significant improvements in device capability are unlikely. Development effort devoted to circuiting techniques (to allow combining large numbers of devices) is needed.

2. Available resources. Test facilities at LASL are adequate for the present. They should be expanded when needs are defined. Manufacturers of vacuum switches and thyristors (e.g., Westinghouse, G.E. Philadelphia) have some capability to test. Rensselaer Polytechnic Institute at Troy, New York, is working on a high speed mechanism — in addition to vacuum switch manufacturing efforts.

3. Program. First, detailed requirements must be defined, then specific device development needs can be defined.

In any case, vacuum switch development should be directed and encouraged with minor funding (\$50 thousand per yr) at present. Also,

a circulating technique effort for commutating either vacuum or solid state switches should be administered and funded by a single agency (present efforts are diffuse).

4. Switch-commutating switches for TNS. To switch high voltage dc (OH, TF, etc.), usual techniques involve a "commutating" circuit whose purpose is to divert current from the main switch long enough to allow the main switch to open (de-ionize, recover, etc.). The commutating circuit switch has to carry currents of the same magnitude (usually slightly larger) as the main switch and withstand voltages ranging from as high as to several times higher than those the main switch must withstand.

All proposals to date for the commutating switch involve ignitrons or semiconductors. Another device — the hydrogen thyatron — should also be considered. English Electric Valve Company has commercially available tubes capable of voltages to 160 kV and currents of 6000 A; lower voltage tubes with 10 kA capability are available. These are repetitive-pulse current ratings; at a 10 sec or more pulse interval, ratings increase 10 times. Hydrogen tubes are suitable for the short pulse (10s to 100s of μ sec) requirements of the commutating switch.

5. Nonlinear resistors for TNS coil circuits. Two areas — general transient suppression and coil voltage clamping (to extend the high plasma current portion of the OH pulse) — require nonlinear resistors. Westinghouse and International Rectifier make selenium devices capable of up to 80 to 100 A at 75 V per device. The most promising varistors are a family made by G.E. Pittsfield. These are zinc oxide devices capable of 20 kJ (vs 1 kJ for selenium) at up to 10 kA per device. Further development to increase device capability would be desirable to avoid the cost and reliability shortcomings of multiple device systems.

6. Neutral beam switching approaches. There exist several relatively untested proposed alternatives to vacuum tube switches. Because of uncertainties associated with 400 kV vacuum tubes, these alternatives must be evaluated and one or two of the most promising funded for further development. Present efforts at LBL, LLL, and Argonne are known; there are approaches in radar technology that may be available.

4.11 Plasma Heating (WBS 24)

A. C. England G. Schilling
W. L. Stirling

February 1977

4.11.1 Summary

Present physics understanding is insufficient to develop specific criteria for plasma heating. Two technology paths should be included in the TNS R&D program — neutral beam injection and radio frequency heating. The required heating method could be a combination of the two.

4.11.2 Summary of neutral beam heating

The accumulated experience of existing neutral beam heating experiments indicates that the technology base exists for application to TNS. The major problem is one of extending the beam technology beyond the presently existing levels of energy and efficiency.

Positive ion beam generation, as exemplified by the LBL and ORNL goals of 120 keV, 50 A, 0.5 sec for TFTR, may be extended to the presently perceived "threshold" goal of 150 keV for TNS. The pulse length must be extended to the TNS beam time in the range of 5 to 10 sec, whereas the total injected power requires an increase in ion current to 100 A per injector as well as an increase in the number of injectors per beam line.

Direct recovery of the residual ion energy should be developed for TNS. The increase in electrical efficiency of the injectors by a factor of about two does not reduce the total number of injectors and beam lines needed, but it does reduce the requirements for the expensive high voltage power supplies feeding the injectors. The resulting cost savings will be appreciable.

Negative ion beam generation is still in its infancy with the initial double-charge exchange experiments at LLL, direct extraction experiments at BNL, and thoughts on direct extraction at ORNL. At 150 keV, the increase factor of about 3 in fast neutrals per ion over the positive ion approach increases the mechanical and electrical beam

system efficiency. Fewer beam lines and less electrical power will be required, giving considerable TNS cost savings. At the higher injection energies potentially needed for TNS — above 200 keV — the reduced positive ion efficiency makes a negative ion approach essential for the generation of adequate amounts of neutral beam power.

4.11.3 Summary of RF heating

RF experiments already performed on small devices at half the field of TNS have demonstrated that a physics base exists. Extrapolations to TNS show that both ICRF (ion cyclotron range of frequencies) and ECH (electron cyclotron heating) would be satisfactory supplemental auxiliary heating schemes in conjunction with neutral beam injectors. Other existing programs of RF heating (e.g., lower hybrid and Alfvén wave heating) may show promise in CY 1978-1980.

The TNS requirements for plasma RF heating may vary from profile control and preionization through heating of particular plasma components to bulk plasma heating. The proper ratio (RF/NB) should be determined from better physics understanding by CY 1980-82.

A TNS technological supporting base is now being developed in two major areas. The first is a 2-MW, 55-MHz ICRF experiment for PLT to begin in CY 1979 or later depending on their present NB program. The second is the development of a 120-GHz, 200-kW continuous wave (CW) microwave tube for ECH and upper hybrid heating (UHH) by CY 1979.

Adequate funding is presently available for the program of tube development. Presently a 28-GHz, 200-kW continuous wave device is under test as the first phase of this program. Tube development for ICRF is not presently needed. Subsequent development efforts which can be addressed later may be focused to TNS particular requirements such as reliability, control, and maintenance. Once a particular type of heating is selected, parallel developments should be focused on components such as microwave windows, insulators, and control circuits. The statistical reliability of a large number of microwave tubes will require development efforts for ECH.

Figure 15 is the program chart for plasma heating.

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Fig. 15. Program chart for plasma heating (WBS 24).

4.11.4 Discussion of neutral beam heating — W. L. Stirling

At 150 keV, the threshold goal for TNS, a positive-ion-based system requires about 50 A of extracted beam to inject 1 MW of neutral power (assumed to be all D). The ratio of neutral power to extracted power is about 13%. For reference, a PLT beam line will produce the 1 MW of neutral power at 150 keV. Thus we need 75 such beam lines on TNS to achieve 75 MW of injected neutral power, which is a physical impossibility. These beam line boxes require a circumference of about 114 m, but only about 57 m exists around the machine at $R \cong 9$ m where the boxes are located.

Increasing the source size to 100 A and mounting 6 sources to the box, 3 vertical and 2 horizontal, there would be 6 boxes or beam lines which would take only about 1/2 of the torus for access. Each box would have from 6 to 10 PLT-size cryopumps, depending upon whether the gas cell is close-coupled. Again comparing to PLT, the cost at 40 keV (H^+) was \$2/watt of injected neutral power. At 150 keV (D^+) the conversion efficiency is down by a factor of 3, but the loss is made up by the increase in energy per particle by 3.75. Also, the cost of high voltage supplies at 150 kV is about a factor of 2 greater than at 60 kV (taken from comparisons of actual prices of our 60-kV and 150-kV supplies). The increase in cost of 150 kV over the PLT value is a factor of 1.7. Thus the cost for TNS is \$125 million.

Considering the methods of power loss in the beam system, one can hope for no more than cutting the cost by about half with direct recovery in a positive ion system. (About 80% of the extracted power is transmitted through the gas cell, and 20% of that is in neutrals. Thus at most 64% of the applied power is recoverable.) It should be noted that the reduction in power usage does not reduce the size of the beam lines. Size is determined by gas pumping requirements, which are not affected by direct recovery.

Other or additional savings may be realized by (1) negative ions with gas neutralization cell (reduce costs by about 1.5) (2) negative ions with direct recovery (reduce costs by about 2.4), and (3) negative

ions, direct recovery, and very highly ionized plasma neutralization cell (reduce costs by about 3). The plasma neutralization cell is also an R&D project.

Comparative power losses. If the loss performance of the positive ion system is called unity, the following systems have the fractional loss of the positive ion system (only 150 keV).

Improvement factor	1 Positive ions	1
	Negative ions	.68
	Positive ions and recovery	.54
	Negative ions and recovery	.42
	3 Negative ions (plasma cell) and recovery	.34

Neutral beam heating technology was divided into three categories in order to consider the relevance of the programs to TNS needs: (1) positive ions, (2) negative ions, and (3) direct recovery. The relative merits of positive ions vs negative ions are shown in the questions below, which are discussed for each type of ion. Direct energy recovery is also discussed and the desirability for increased efficiency becomes apparent in the accompanying beam line cost estimate.

1. Positive ion technology. The knowledge necessary to produce injectors and beam lines — extrapolated from PLT and TFTR — is in hand and is understood. There are adequately trained people both at ORNL and LBL. Furthermore, there are adequate facilities available to test the ion injectors. The operating funds for national R&D are consistently running about 30% low each year (about \$10 million per year instead of \$13 million per year).

In assessing the program needs, there may be a vying for resources between TFTR and TNS because TNS is an extension of TFTR technology. The beam program is well-ordered but definitely favors TFTR, and the program is well-coordinated.

This program should be redirected to place greater emphasis on development in the 150-keV to 300-keV range. The commitments of LBL to current projects place them in a limited R&D position which favors a refocusing of program effort at ORNL to TNS requirement. To proceed

aggressively toward TNS goals, there should be an immediate increase by about 30% in operating money. In addition, an MDF proposal for a 300-keV shielded facility should be approved without delay.

2. Negative ion technology. The increased conversion efficiency of negative ions to neutrals over that obtained for positive ions to neutrals (60% for negative ions compared with about 20% for positive ions at 150-keV D^0 and about 7% at 300-keV D^0) makes a negative ion system the preferred one. Unfortunately, negative ion source technology is in its infancy compared with that of positive ions.

The real knowledge necessary to produce negative ion beams is not in hand, and there are too few people trained to the "state of the art." The necessary test facilities are not in hand since the 200-keV test stand at LLL is not available due to heavy commitments to current projects. The operating funds for R&D are severely limited. The program is properly directed but at a very low intensity. To meet TNS needs, there should be an effort parallel to the positive ion program. The negative ion program is too small to require significant coordination of effort. The program should be directed with an emphasis on TNS needs, whereas now it is testing various independent concepts. Reorganization to establish definite TNS goals and a responsible party is necessary. Funding should be comparable to positive ion development.

3. Direct energy recovery. The prohibitive cost of present state-of-the-art positive ion injector systems for 150-keV applications makes development of increased efficiency mandatory. Unfortunately, R&D in this area is even weaker than the negative ions program. Except for about a 3-man effort at LLL, the base is nonexistent. The need for energy recovery depends upon choice of positive or negative ions. If the decision is for positive ions, a great deal of emphasis is needed on energy recovery.

4.11.5 Discussion of RF heating — A. C. England

In the range of frequencies appropriate for ECH and UHH (50 to 150 GHz), there is a development program based on the gyrotron or gyro-klystron principle. This program is presently funded to demonstrate a

CW tube in a low frequency range at 200 kW for Elmo Bumpy Torus (EBT) application. The continuing program then addresses demonstration of a 200-kW CW tube at 120 GHz in CY 1979. There are people trained in this area; there are facilities available; and adequate funds exist for the present program. Component development exists in concert with tube development. Because of the rather special nature of a waveguide window on a plasma device, this problem may need additional development beyond that already in existence.

In the lower frequency ranges considered for RF heating of tokamaks — LH (1 GHz), ICRF (25 to 100 MHz), Alfven (1 to 10 MHz and lower) — tubes already exist with the requisite power. Some specific problems would require effort, such as window and other component development. These problems have simply never been addressed, and thus have never been solved, and are probably small in comparison with corresponding problems in the ECH and UHH range.

The specific ECH source development in question is directed toward the needs of the EBT program. A definitive experiment utilizing a 28-GHz device similar to that developed for EBT could be performed on ISX or D-IIa. Further developments in tube reliability are required for multiple-tube, 2-MW, 120-GHz sources for EBT-II. TNS requirements for an order-of-magnitude greater power levels would require correspondingly greater reliability. A device producing power at the 200-kW level at 120 GHz would find application to both EBT and tokamaks. The nature of the present devices restricts the power per tube to this kind of limit. Application to bulk plasma heating in TNS would therefore require 250 to 500 tubes at estimated capital cost of \$500 thousand per tube installed. The large number of tubes would require extremely good reliability and involve additional problems in control and maintenance. Additional funding for development at this time and coordination or redirection of the program will not aid the present schedule for producing demonstration tubes, but could conceivably affect future reliability effort.

Similar questions can be addressed for the other frequency ranges. The program needs require assessment. There is presently no ordered and

coordinated program for the development of the sources and components for RF heating experiments at the lower frequencies.

For microwave tube development for ECH experiments, no redirection is presently needed. The need for redirection and corresponding reorganization and funding should be reassessed after the present development program has produced the first operating devices at 120 GHz. Reliability requirements implied by the very large number of tubes required for ECH on TNS are extremely high. Prospects for attainment of necessary reliability in conformance with TNS schedule are judged poor under optimum circumstances. Applications such as profile control and preionization would require a much smaller number of tubes. Reliable operation of such systems in conformance with the TNS schedule is much more probable.

Again, because of the much less complex technology required for the lower frequency experiments, the problems are much smaller. Direction and organization may be required for TNS application for specific relatively small-scale technological development programs (e.g., in microwave windows at 1 GHz, insulators for coil supports near walls, and component development).

4.12 Remote Servicing (WBS 25a)

P. T. Spampinato

February 1977

4.12.1 Summary

The technology base for remote servicing concepts and equipment does exist to initiate TNS conceptual design, even though it is centered on the fission and aerospace communities. Although there presently appears to be no focus on fusion reactor problems, a full assessment is expected from the McDonnell-Douglas Corporation in early FY 1978 (under ERDA contract).

Several additional inputs are expected to support TNS, namely the TFTR development and demonstration during TNS conceptual design and the JET design experience in 1980/81. It is essential that TNS establish its own program of remote systems verification after TNS conceptual design. This program will be accomplished with a series of mockup systems to be completed before a final design review. Specific areas to be investigated are handling of large components, remote cutting and welding, leak detection, and viewing systems. This TNS development program coupled with liaison to ongoing TFTR development and demonstration will provide a sound basis for the device design. Additional comments are noted in the machine structure discussion.

Figure 16 is the program chart for remote servicing.

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Fig. 16. Program chart for remote servicing (WBS 25a).

4.13 Fuel Handling (WBS 25b)

J. S. Watson

February 1977

4.13.1 Summary

The technology base exists for the design and manufacture of the fuel handling system. However, the principal need for the design of this system in TNS is an overall demonstration on a reasonable scale which combines all the elements of the fuel processing chain. This demonstration is the function of the Tritium Systems Test Assembly (TSTA) and will need to be closely coordinated with the TNS program. The fuel handling system consists of D-T purification equipment, isotope separation equipment, storage tanks, transportation station, and monitoring and control equipment. There is a substantial amount of knowledge and experience at various ERDA laboratories and plants in deuterium and tritium handling. For this reason, fuel handling is probably one of the best understood of the TNS auxiliary systems, but a meaningful demonstration is essential.

Figure 17 is the program chart for fuel handling.

4.13.2 Discussion

The components of the fuel handling system are the D-T purification equipment, the isotope separation equipment, fuel storage tanks, the fuel receiving (shipping) station, and the monitors and analytical instruments which provide inventory control. Three items often associated with the tritium or fuel systems (vacuum pumps, fueling devices, and atmospheric cleanup equipment) are discussed with other systems. Similar development needs of these components make it more convenient to consider them with the other systems. The fuel handling system as defined here is probably one of the best understood systems for TNS. We have working models of similar components at various ERDA laboratories and plants, although they do not always function under conditions identical to TNS. There is a substantial amount of knowledge and experience in handling

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Fig. 17. Program chart for fuel handling (WBS 25b).

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tritium and deuterium which can be applied to TNS. We thus have a good basis for beginning design of TNS, and no substantial research and development on these particular components is needed to establish the feasibility of TNS. Existing R&D programs funded by other ERDA divisions (Physical Research, Military Applications, Waste Management, and Production) will aid TNS. These programs, of course, are not focused on TNS, but they will provide desirable (if not necessary) improvements in the physical data and techniques which can be used by TNS.

Although no substantial research and development program is needed for the fuel handling components (excluding vacuum pumps and pellet injectors), this is an extremely critical system to TNS, and a realistic demonstration of the fuel handling system (along with vacuum pumping and atmospheric cleanup) will be necessary. Many of the safety problems and most of the environmental problems of TNS will be in these components. Failure of some of the fuel handling components could not only stop the immediate TNS operations, but they could seriously contaminate the device and delay start-up, perhaps indefinitely.

This demonstration is the function of the TSTA, which is planned for construction at LASL. It will be necessary for the TSTA and the TNS designs to work very closely together to obtain the most realistic demonstration possible in TSTA. It would be preferable to have an exact full-scale demonstration of all components of the main vacuum system, fuel handling system, and atmospheric cleanup system in TSTA. Unfortunately, since the design of TNS and TSTA must proceed in parallel, there will be no way to provide a final design to TSTA at this time. We know with considerable confidence the general function of the fuel handling system, and we can even say which techniques are most likely to be suitable for purification, isotope separation, etc. We cannot, however, accurately specify the throughput, the gas composition, or the purification and isotope separation requirements. These design criteria all depend upon other portions of the TNS design and upon the physics of the device. Since many of these parameters will only become known over the next few years, the design of TSTA will have to begin with a set of

reference conditions contributed from the TNS design teams, and close cooperation will have to be maintained between the TSTA and the TNS teams to insure that changes in the TNS design are taken into account in TSTA. The TSTA design should begin on the basis of a vacuum pumping speed of approximately 40,000 liters/sec from a 1-m duct. This has a high probability of being close to the size of a single TNS pump. Although there are large uncertainties in the pumping speed required for TNS, the 1-m pump (~40,000 liters/sec) corresponds to the largest-diameter duct which will likely fit between two TF coils. Although the TSTA cannot be modified to fit every minor change in TNS, it must respond quickly to any major changes and consider how the data from TSTA can answer questions raised by even minor changes in TNS.

The major program which provides needed support to TNS in fuel handling is the TSTA demonstration. That program should be sharply focused on TNS, and cooperation between the two programs is crucial. This should be accomplished by voluntary cooperation and by representation of the TNS design teams on any steering or review committees established for TSTA. In addition, there should be frequent contact, principally by phone but also including onsite visits. All pertinent reports should be exchanged as rapidly as practical. It is also crucial that TSTA provide the demonstration in time to have an input into TNS. The required schedule is tight, and any substantial delays would reduce the effectiveness of TSTA in providing information on the presently postulated TNS schedule.

4.14 Main Vacuum Systems (WBS 25c)

R. N. Cherdack

February 1977

4.14.1 Summary

The technology base exists to initiate conceptual design for the main vacuum systems (MVS). Cryocondensation and cryosorption pumping techniques have been identified as having the greatest potential to satisfy TNS vacuum pumping requirements for both the torus vacuum vessel and neutral beam vacuum chambers. However, a program to develop configurations to pump helium in the presence of hydrogen isotopes is necessary because existing designs will not work. Difficulty in using commercial cryopumps for pumping mixtures of helium and hydrogen isotopes has been identified and demonstrated experimentally at ORNL.

Additional uncertainties relating to criteria or physics requirements such as particle flux to be handled and allowable pressure at the plasma boundary must be resolved for the conceptual design.

Figure 18 is the program chart for main vacuum systems.

4.14.2 Discussion of torus vacuum system

1. Function. The torus vacuum system (TVS) will be used to maintain the appropriate pressure in the vacuum vessel. Its functions include removal of vessel outgasses, pumpdown of the vessel between pulses, and probably, but not certainly, removal of plasma exhaust during a pulse.

2. Criteria. Several generic criteria for the TVS have been established including ultimate very high vacuum capability; very high pumping speeds at reasonable cost; minimum hazard, loss, and difficulty in handling tritium; no backstreaming; flexibility in location and arrangement; and the ability to pump helium. It is widely accepted that cryocondensation and cryosorption are the techniques which best meet these generic criteria.

Quantitative criteria for the TVS have not yet been developed. Criteria covering pumpdown time between pulses and ultimate base pressure

T N S PROGRAM SCHEDULE

Fig. 18. Program chart for main vacuum systems (WBS 25c).

with respect to vessel outgassing and leakage can be developed early in the conceptual design. These criteria are expected to be somewhat arbitrary but not particularly difficult to meet. The major uncertainties concern pumping during the pulse and include the allowable pressure in the region being pumped and the number of particles to be pumped. These parameters are dependent on plasma transport phenomena, impurity control and fueling techniques, and plasma vessel and/or divertor burial chamber design.

3. Data base. The design and manufacture of cryopanel and cryosorption panels and pumps is fairly well established. However, pumps or systems of pumps which can remove helium in the presence of large quantities of hydrogen isotopes have not yet been designed. ORNL's Chemical Technology Division proposed an aggressive program in this area, but funding cuts of 75% have reduced the goals to continued investigations of existing commercially produced equipment under various conditions. Commercial equipment has already been demonstrated to be inadequate for the particular task of pumping helium in the presence of large quantities of deuterium.

A pump which is at least similar in concept and scale to that required in TNS should be incorporated into the demonstration of a plasma exhaust recycling system in TSTA. Frequent and fast regenerations of such a pump should be performed to prove reliability. For conclusive demonstration of reliability before completion of Title I design of the device, development of the compound pump should begin before FY 1978.

At this time, there are very few people skilled in design and manufacturing of cryosorption panels although a large number of people are capable of producing system designs which incorporate such equipment.

There are vacuum component development programs related to neutral beams at ORNL, BNL, and LLL. Although information and experience gained from these programs will provide a useful pool for vacuum system designs, they do not address the issues outlined in the preceding paragraphs.

It would also be useful to develop designs which are optimized with respect to refrigeration requirements. Such optimizations would probably

require a mixture of 77 K, 15 K, and 4.2 K panels. Such optimizations will be sensitive to the detailed TNS design, but basic data concerning emissivities, reflectivities, transport through chevrons, etc., which can be obtained in a development program would be necessary. The development of designs utilizing materials which will lead to minimal neutron heating and activation would be beneficial.

Such research and development could be incorporated into any existing programs concerned with the design, fabrication and testing of cryopanel and cryosorption panels.

Large fast-acting dampers may be needed to impede vacuum pumping on the plasma vessel just before a pulse, and similarly sized, tight-sealing isolation valves will be needed for regeneration. Development of such devices, particularly for noncircular ports, should be conducted before they are required for the TNS torus vacuum system. Development work could be performed at qualified vacuum equipment manufacturers.

4.14.3 Discussion of neutral beam vacuum system

1. Function. The neutral beam vacuum system (NBVS) is required to maintain acceptable pressures in the neutral beams. The allowable pressure is determined by losses which can be tolerated in the grid and drift tube regions. Sources of gas include the ion source, the neutralizing cell, and material from the torus flowing up the drift tube. When the source terms and allowable pressures are determined by the beam design, they will in turn determine the required speed for the NBVS.

2. Criteria. Generic criteria are similar to those from the torus vacuum system (TVS) and include ultimate high vacuum capability, very high pumping speeds at reasonable cost, minimum hazard loss and minimum difficulty in handling tritium, no backstreaming, and flexibility in location and arrangement.

Again, it is widely accepted that cryopanel and cryosorption panels are the leading techniques. Depending on plasma transport properties and drift tube conductances, helium may have to be pumped by the NBVS. If this is the case, then a compound pump similar to that for MVS may be required.

3. Data base. Design and manufacture of cryopanel and cryosorption panels is well-established. Improvements are possible and may lead to worthwhile increases in performance or reduced refrigeration loads. (See Sect. 4.14.2 for this and for hardware development needs.)

Vacuum component development programs at ORNL, LLL, and BNL are working on panels for NBVSs. The components of an NBVS must be demonstrated in actual use in a beam line to determine their compatibility with gas and ion species and heat loads which exist in a beam line. Existing programs are expected to address this problem up to TFTR-size beams. Extrapolation to TNS energies and power levels are not expected to require major changes. However, the heat loads and material damage effects from neutron and gamma radiation must be investigated. Geometries must be estimated so that neutronics calculations can be made of approximate fluxes. Heat loads can then be calculated and the likelihood of damage assessed. Of particular interest may be the bond of the molecular sieves to panels on cryosorption devices. Some irradiation experiments may be necessary. Beam line vacuum component development, TNS shielding and neutronics, and fusion materials teams should collaborate on this effort.

4.15 Heat Removal (WBS 25d)

C. G. Lawson

February 1977

4.15.1 Summary

The technology base exists to initiate the conceptual design for the heat removal systems. The development and demonstration of refrigeration and cryogenics will be directly derived from the LCP program at ORNL and through additional programs at BNL and Fermi National Laboratory (FERMILAB). Currently, existing systems are 1/10 of TNS size requirements, and the technology base for extrapolation exists. The development program should be focused primarily on equipment reliability and scaling and will be required during the preliminary design phase. This could be handled through the manufacturer of this equipment. Additional technological resources are available from other industrial manufacturers and cryogen producers.

Figure 19 is the program chart for heat removal.

4.15.2 Discussion

The TNS fusion experimental facility utilizes liquid helium under forced flow as a coolant through the superconducting cables of the toroidal field magnets. The refrigeration system, liquid helium pumps, and other hardware associated with the piping systems require development and testing to achieve the high reliability levels required in a fusion device. There are programs currently performing the work of developing the required hardware and performance characteristics.

The refrigeration equipment being developed for Isabella at BNL and the Energy Doubler at Fermilab are, respectively, about 3 and 10 times larger than the nominal 1.5 kW refrigerators now being built for Fermilab, ORNL, and LBL. This equipment is being built by CTI of Waltham, Massachusetts. Future potential competitors in the United States include Airco, IGC-BOC combined, Linde, CVI, Gardner and Air Products, as well as foreign suppliers.

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Fig. 19. Program chart for heat removal (WBS 25d).

The Large Coil Project at ORNL is in the process of developing liquid helium pumps, high current superconducting leads, and other hardware. A forced flow conductor is being developed with U.S. industry and the MIT National Magnet Laboratory.

Reliability information from industrial users of cryogenic equipment is being assembled and analyzed by Air Products Company, The Garrett Corporation, and the National Bureau of Standards at Boulder, Colorado, under subcontract from ERDA. Additional hard data that is directly relevant to TNS operation will be obtained from the LCP at ORNL from FY 1978 onward. These data will be obtained by 1980 in time for advanced engineering and Title I and Title II design of TNS, assuming funding continues as planned during 1978 and 1979.

The above-mentioned programs have been initiated as a result of TNS and EPR studies on tokamak machines or to support hardware development and reliability studies for superconducting transmission lines. Accordingly, the focus to high reliability and tokamaks has already been achieved. It is likely that additional refocusing towards evaluation of systems reliability and computer control of cryogenics systems will be required. No increased funding or new programs beyond those planned is required.

4.16 Experimental Cell Ventilation (WBS 25e)

R. N. Cherdack

February 1977

4.16.1 Summary

Research and development is not anticipated for the ventilation of the experimental cell. The preliminary design of this system is dependent upon the choice of a TNS baseline configuration; therefore no schedule or detailed discussion need be presented except for the following.

The design of the experimental cell ventilation system is very dependent on the device and facility design, and it is assumed that the structure will be very leak tight. Major concerns in this system design include containment of activated air and tritium leaks. Both of these demand the leak tightness suggested above along with a well-elevated stack release point.

A tritium cleanup system(s) as discussed under fuel handling will be required to reduce the consequences of tritium releases from the device. Air activation effects can be reduced by using low ventilation rates, holdup ducts, increased shielding around the device, and controlling the composition of the cell atmosphere. Excluding oxygen from the cell will eliminate nitrogen-16 production and also most fire and explosion hazards. One particularly attractive alternative is maintaining a high vacuum in the cell. The vacuum system will be compatible with a tritium cleanup system.

4.17 Radioactive Waste Handling (WBS 25f)

R. N. Cherdack

February 1977

4.17.1 Summary

It is not anticipated that research and development is required for radioactive waste handling on TNS; therefore, no schedule or detailed discussion is necessary.

Contaminated materials will consist of portions of the device itself which must be disposed of and also of those components which become contaminated through contact with the coolant. The disposal of the radioactive wastes is expected to be performed using techniques well-established in fission programs. The remote handling equipment required for the repair or removal of these parts is addressed elsewhere.

4.18 Fuel Injection (WBS 25g)

R. J. Colchin A. T. Mense

S. L. Milora

February 1977

4.18.1 Summary

The technology base exists to initiate conceptual design for TNS. However, the current program may require modification as physics understanding and design criteria develop. Frozen hydrogen pellet injection has been selected as the concept with the best potential for fueling TNS. R&D programs are under way at ORNL, the University of Illinois, and GA, with the major development effort at ORNL. The knowledge of pellet-plasma interaction is reasonably well-developed, and the technology development program has been planned with logical milestones to demonstrate TNS needs.

Proposed pellet injection velocities are presently limited to <3000 m/sec due to structural design limits of even the most advanced material candidates for the impeller. However, the analytical model predicts required velocities of >10,000 m/sec to penetrate to the center of the TNS plasma. Physics understanding and criteria are required to support trade studies between pellet size and velocity and fuel penetration rate.

Figure 20 is the program chart for fuel injection.

4.18.2 Discussion of the physics of fueling — A. T. Mense, R. J. Colchin

I. Plasma models

- A. Gas puffing and wall recycling
- B. Pellet injection and wall recycling
- C. High energy injection
- D. Clusters

II. Research required:

- A. Gas puffing and wall recycling
 - 1. Determine mechanisms by which neutrals are reintroduced into plasma

Fig. 20. Program chart for fuel injection (WBS 25g).

- a. Gas holdup studies
 - b. Long-pulsed experiments ($\tau \gg \tau_p$)
 - c. Different walls, limiters, and wall treatments
- 2. Determine effects of gas puffing on disruptive instability and its onset
 - a. Investigate density limit
 - b. Investigate the effects of different heating mechanisms in concert with puffing to attain higher densities
- 3. Determine how this works in presence of divertor
- B. Pellet injection
 - 1. Ascertain if basic ablation and shielding physics model extends up to higher T_e and N_e plasmas
 - 2. Determine how to make larger and faster pellets
 - 3. Determine if pellets undergo a neutral particle phase during ablation process
 - 4. Determine if pinch effects can provide central fueling, thereby lessening penetration requirements on pellets
- C. High energy injection (beams ≥ 10 keV)
 - 1. Decide in what phase of the start-up cycle (and/or burn) beam fueling would be consequential
 - 2. Investigate the problem of thermally unstable plasma energy after ignition
 - 3. Investigate the possible sputtering problem with beam deposition near plasma edge
- D. Clusters
 - 1. Investigate the penetration and deposition problems (are they the same as with beams?)
 - 2. Have fast injection

III. Research projects

- A. Gas puffing and wall recycling
 - 1. Develop long-pulsed tokamak operation
 - 2. Investigate different wall materials and treatments
 - 3. Use different heating schemes to determine density limits
 - 4. Investigate the effect of divertor on gas puffing scenario
- B. Pellet injection
 - 1. Use larger and faster pellets in any present and currently planned tokamaks, including divertor tokamaks
 - 2. Develop acceleration techniques for pellets

- C. High energy injection
 - 1. Study impurity trapping and production with and without divertors when beams are used to fuel
 - 2. Study the thermal instability problem — probably only diagnosable numerically or in a fusion ignited plasma
 - D. Clusters
 - 1. Other schemes more viable as alternatives
 - 2. Some work being developed for use on TFTR
- IV. Present program relevance
- A. Gas puffing and wall recycling
 - 1. All present programs very relevant to this problem, particularly in how puffing effects density limit in tokamaks (Alcator - C/test gas puff in high field)
 - 2. Gas puffing with neutral injection very important but also should be studied with RF heating
 - 3. Gas puffing with divertor must be tested (PDX/ISX-II)
 - 4. No long pulsed-time tokamaks yet planned (flat top > 1 sec) — might speak well for a superconducting toroidal field tokamak; might be tested in PLT or PDX
 - B. Pellet injection
 - 1. If gas puffing not adequate and/or divertors required, pellet injection the most viable alternative
 - 2. No current experiments planned to test "neutral phase" of ablation physics (could be done in ISX, PDX, or PLT)
 - C. High energy injection for fueling: PLT 40 keV, ISX-II should be able to address this concept
 - D. Clusters
 - 1. No projects in United States
 - 2. A question of relevance when compared with pellet fueling
 - 3. Information may come from TFTR program

4.18.3 Discussion of the technology of fueling — S. L. Milora

The people, knowledge, and facilities exist with which to begin a TNS pellet fueling effort. In fact, pellet fueling programs initially grew out of the concern that ignited plasmas might prove difficult to refuel. Consequently, all of the existing programs have as their focus the attainment of an advanced pellet injector for use in a reactor,

although there is disagreement as to which concept would most likely be successful. In this respect, little overlap exists in the three or four programs addressing this problem.

As concerns the funding situation, it is only adequate to support the ten or so individuals conducting the research. Current funding levels are estimated to be about \$600 thousand with funding supplied by ERDA, NSF, and EPRI. The principal institutions involved are ORNL, University of Illinois, and GA; but the major development effort is presently located at ORNL. These programs are still in the formative stage, as is the concept of fueling in general. Initial pellet injection experiments have been performed on ORMAK by ORNL and University of Illinois personnel but the apparatus used for injection is an experimental tool that does not have viable refueling capabilities. Still, these experiments were valuable in that a model was developed that explained the observed results. In this respect, the knowledge of the pellet-plasma interaction is fairly well developed. Several analytical studies which have addressed the technological problems associated with pellet fueling point to a characteristic injection velocity greater than 10,000 m/sec with about 1-mm pellets. These projections are based on the unsupported assumption that pellets must penetrate to the plasma center. In these studies, the sizes of pellets have been limited to values that are not expected to make major perturbations on the plasma. The technology for accelerating hydrogen ice to hypervelocities does not exist, and it is highly questionable whether 10,000 m/sec with macroscopic pellets could ever be attained even with greatly increased funding levels. It is unrealistic to assume that, at the present funding level, such injection devices could be developed in the short period of time allotted. Such an assumption is contrary to previous experience.

The situation is not this grim if we begin now to reconsider the problem of fueling in general. Additional physics understanding as to what constitutes fueling is badly needed, and some realistic fueling criteria need to be developed. For example, if pellets are required to

penetrate only halfway into the plasma, a severalfold reduction in injection velocity would result (based on analytical models). If larger pellets were allowed, a further reduction would result. Such allowances would greatly alleviate the technological difficulties to the point that pellet fueling would be viable at a reasonable funding level and schedule.

4.19 Instrumentation, Control, and Data Systems (WBS 26)

W. R. Becraft J. L. Dunlap W. R. Wing

February 1977

4.19.1 Summary

There are two major gaps in the technology base available for the IC&D systems for TNS:

1. plasma shape sensing and control and
2. abnormal discharge control.

The feedback control of the plasma configuration is a requirement and becomes more important as burn time increases. Most fusion experimentation to date has used open loop control.

The first emphasis in this area must be on physics understanding: the definition of the plasma configuration and transients and their relationship to sensor outputs and controllable energy inputs. Experimentation to clarify these parameters can best be achieved with a new flux conservation test device (FCX) in addition to results from existing experimental programs (i.e., ISX, D-IIA, PLT). A dedicated plasma theory-simulation effort must be devoted to this investigation.

A parallel technology effort is required to define the transient capability limits of the component subsystem and the transfer functions achievable. These evolving data along with the output from the physics experiments, theory, and simulation will provide systems modeling for bracketing the control laws and hardware necessary for all anticipated operation.

The supervisory computer, data handling systems, and software procedures can be developed from the existing technology base.

Figure 21 is the program chart for instrumentation, control, and data systems.

4.19.2 Discussion

Table 9 presents in a condensed form the problems related to the I, C, and D systems.

Fig. 21. Program chart for instrumentation and control (WBS 26).

Table 9. Problems related to instrumentation, control, and data systems

TNS ^b No.	Discharge stages	Control algorithms, sensors, and control methods needed	
		Size-related	Shape-related
1.1	Controlled breakdown		Will nonuniform preionization be necessary? How will we control it? Inputs needed: theory-simulation FY 77-79, FCX ^a experimental results FY 80-81
1.2	Density buildup	Will "gas puffing" work in large machine?	
1.3		If not, other control method needed. Inputs needed: D-III, PDX FY 79-80 (natural fallout of programs)	
2.	Heat to high- β ignition	Need injection or ECH or both? How do we control them? Inputs needed FY 79-81: theory-simulation and PDX, PLT, EBT-II (natural fallout)	Degree of equilibrium sensing necessary? Are heating and position-shape control separated problems? Will rate and position of power deposition have to be controlled as part of the equilibrium feedback loop?
3.	Maintain equilibrium	What is "rate-of-loss" of equilibrium? Amenable to "low frequency" control? Inputs needed FY 78-82: theory-simulation and natural fallout from D-III, PDX, TFTR	Need <u>much</u> input from theory-simulation; need input from experiments: ISX, FCX FY 77-82 (natural fallout)
4.	Power removal	Will thermal instabilities be a problem? Need efficient means of control. Inputs needed FY 78-82: theory-simulation and natural fallout from TFTR	
5.	Ash removal		
6.	Fueling	Will "gas puffing" work in large machines? To what degree can it interact with power removal and equilibrium? Inputs needed FY 77-82: theory-simulation and natural fallout from D-III, PDX, TFTR	
7.	Impurity control	Divertors vs flow reversal — here all questions from fueling and equilibrium come up again. Special needs from ISX, FY 78+	Divertors vs flow reversal — here all questions from fueling and equilibrium come up again. Special needs from ISX, FY 78+
8a.	Termination, normal	Controlled shutdown: electromagnetic recovery? All equilibrium questions get worse. Need experiments: TFTR may need redirection and FCX more money	Equilibrium may be very difficult to control in conjunction with EM power recovery. Need FCX FY 80-81
8b.	Termination, abnormal	On abnormal shutdowns, need proven algorithms for sensing approaching need for shutdown, i.e., approaching end stops of proportional control system. Need SCRAM methods which protect people and investment	

^aFlux-Conservation Test Device.^bSee Table 1 for definitions.

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